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University — Université

University of Alberta

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

MSc

Year this degree conferred — Année d'obtention de ce grade

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The Late Quaternary Geomorphology of Elk Island National Park, Central Alberta

by

Donald Brian Jennings

C

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Geography

EDMONTON, ALBERTA

SPRING 1984

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Supervisor

John England

Charles Schweger

Date October 5 1983

DEDICATION

This thesis is dedicated to my late mother who spent countless hours at the kitchen table helping me with homework. Her philosophy that "all you can do is your best, Don" has been a constant reassurance for me.

Abstract

An interpretation of the late Quaternary formation and evolution of the landforms within a *hummocky moraine* tract is the basis of this thesis. The research focuses on an area now occupied by Elk Island National Park in the northern portion of the Cooking Lake moraine, central Alberta. The characteristics of the study area are considered within the context of relevant geomorphologic and climatic interpretations for central Alberta. These are also used in the formulation of a geochronologic model applicable to development of the study area landforms and sediments.

The major landforming processes of this *hummocky moraine* tract were generally governed by the chaotic disintegration of an isolated mass of stagnant, glacier ice. Accordingly, complex associations of landforms and deposits characterize the study area. Sedimentation and resedimentation mostly occurred in a dynamic superglacial environment. The formation of the morainic landforms was predominantly by a *let-down* mechanism. Simply, a primary, unequal debris distribution on the glacier surface allowed depressions to become collection zones for sediments transported by mass movement and water. As the buried and supporting ice melted out the sediments were deposited and the relief was *inverted*. The accumulated diamictons and lacustrine sediments of the former depressional areas now comprise the bulk of the landforms. The sedimentary sequences observed within these landforms are used primarily to explain the sequence of mass movement (diamicton flows) and pond sedimentation events which infilled the depressions. The shape of the original depression and the configuration of the ice core dictated which of the three main morainic landform types would result (ie. hummocks – circular depressions, uniformly-shaped ice core; prairie mounds – circular depressions, irregular-shaped ice core; ridges – elongate depressions).

The glaciofluvial/glaciolacustrine landforms were also formed in *ice-contact* situations. This is verified by morphological, sedimentologic and structural observations which indicate sedimentation was over or within glacier ice. For example, the glaciofluvial/glaciolacustrine zones are often pitted. In addition, the sediments often contain allochthonous diamicton bodies and secondary structures (e.g. faults).

Finally, a geochronology is outlined for the study area which fits well with the established interpretations of the major late Quaternary events of central Alberta. The

main geomorphologic and climatic-change events are traced from the retreat of the last Laurentide ice sheet through to the present. Radiocarbon dating on mollusc shells (extracted from superglacial lacustrine sediments within the central core of some hummocks) indicates that the most significant landform development must have taken place between *circa* 11,000 years B.P. and *circa* 9,000 years B.P. Therefore, it can now be confidently interpreted that buried stagnant ice remained within the study area long after the retreating Laurentide ice sheet front lay far to the north and east of the Edmonton area. From *circa* 9,000 years B.P. to the present more subtle evolution of the landscape took place. During this period came the deposition of a thin, discontinuous, aeolian mantle. Lake hydrology and vegetation succession were also affected by climatic variations of temperature and precipitation during and after the Altithermal interval of mid-Holocene time.

ACKNOWLEDGEMENTS

Several persons and organizations provided financial, logistical and, perhaps most importantly, moral support throughout the preparation of this thesis. I would especially like to thank my advisor, Dr. Bruce Rains, for his guidance and critical reviews of the manuscript. Despite his busy schedule he was always available for consultation and encouragement. The manuscript also benefited from the conscientious reviews of the other members of my supervisory committee, Dr. John England and Dr. Charles Schweger. Their constructive criticisms added immeasurably to the quality of this thesis.

Financial support from Parks Canada and the Department of Geography is gratefully acknowledged. Thanks also to Dr. England who funded the radiocarbon dates for the thesis. The Alberta Research Council and the Northern Forest Research Station are acknowledged for their support in the drilling programmes.

Special thanks to my colleague Andrew Gambier for his much-needed assistance both during and after the field work. In addition, numerous discussions with Tom Stewart and Dan Smith assisted in the understanding of, respectively, glaciolacustrine sedimentology and palaeoenvironments.

Finally, I would like to thank Teena, who's patience and understanding allowed this work to be possible.

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1. INTRODUCTION

Research for this thesis was carried out in Elk Island National Park and in areas immediately peripheral to the park boundaries. Elk Island National Park has its origins dating back to the turn of the century when it was established by the federal government as the first mammal sanctuary in Canada. At that time elk were rapidly being destroyed and faced regional extirpation. Since its inception the park has grown in size from 4,410 hectares to the present 19,680 hectares. However, the development of the park as a wildlife sanctuary and recreation area has progressed much more quickly than has research into the glacial environment from which it derived the unique physical characteristics. A detailed geomorphological study, including an interpretation of the probable Quaternary evolution of this area, is a logical starting point from which other natural science studies may extend.

1.1 Study Objectives

The objectives of this study are to;

a. genetically classify and map the distribution of surficial deposits and landforms within the study area,

b. critically evaluate existing theories pertaining to the origin and formation of glacially derived landform–sediment associations. The geomorphic processes which will most satisfactorily explain the genesis of such features in the study area will be defined and discussed, and

c. outline an explanatory model of the late Pleistocene and Holocene landform evolution in the area.

1.2 The Study Area

Elk Island National Park is situated in the north–eastern sector of the Cooking Lake moraine complex. The undulating topography of the park forms a forested *island* rising 30 to 60 metres above the general level of the surrounding country with comparatively small local relief (Figure 1.1).

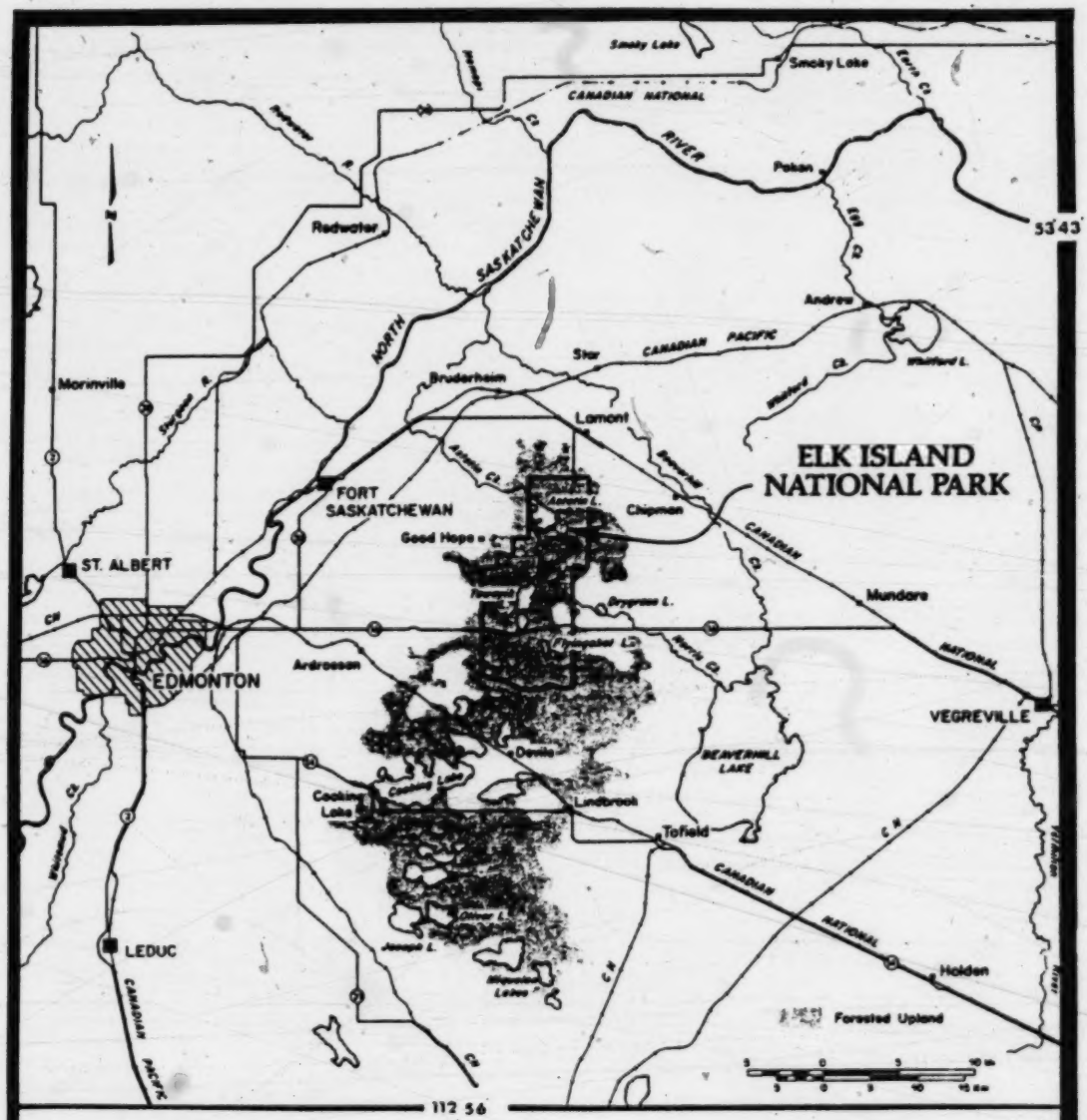


Figure 1.1 Location Map

1.2.1 Physiography

The study area consists of an oval-shaped tract of hummocky moraine overlying a bedrock *high*. Thus, much of the study area exhibits topographic features characteristic of glacier stagnation and subsequent disintegration. The *knob and kettle* topography, with closely spaced hummocks separated by nearly-circular to irregular marshy depressions, morainic ridges and prairie mounds, serves to accentuate the *upland* nature of the area. A salient feature of the topography is the abundance of water-filled depressions. Astotin, Oster, Tawayik, Lower Tawayik and Flyingshot Lakes are some of the larger systems while numerous small lakes occupy kettles and portions of relict channels. The study area is almost devoid of permanent streams or major stream valleys. Elevations within the park are mainly between 710 and 740 metres, with the highest point at 760 metres and lowest point at 704 metres above sea level. Local relief rarely exceeds 15 metres.

1.2.2 Climate

According to the Koppen system of climatic classification (Longley, 1972) the area's climate is microthermal with long cool summers (summers with a mean temperature of the warmest month below 22° C and at least four months with mean temperatures of 10° C or more). The mean annual range in temperature is 32° C. January is the coldest month with mean monthly temperature of about -14° C while July is the warmest with an average temperature of 17° C (Stein, 1976). The long-term mean annual precipitation is about 450 mm. Approximately 70 percent of this falls as rain, mainly during the period April to August (Stein, 1976).

1.2.3 Vegetation

The study area, as part of the Beaver Hills, is classified in the Mixedwood category of the Boreal Aspen Forest Region (Rowe, 1972). The boreal vegetation of this outlier, characterized by forest vegetation which is normally distributed in north-central Alberta, is dominated by aspen poplar (*Populus tremuloides*) and balsam poplar (*P. balsamifera*) on the high ground (Techman Ltd., 1979). Admixtures of white birch (*Betula papyrifera*), white spruce (*Picea glauca*), black spruce (*P. mariana*) and tamarack (*Larix laricina*) are also prevalent where site conditions are suitable (Techman Ltd., 1979). Shrubs, particularly

around the profusion of lakes and ponds, are well represented by dense stands of willow (*Salix spp.*) and alder (*Alnus crispa*). The bog vegetation includes various combinations of Labrador tea (*Ledum groenlandicum*), low cranberry (*Vaccinium spp.*) and cloudberry (*R. chamaemorus*). Details of the vegetation of Elk Island National Park may be found in a report prepared by Techman Limited (1979).

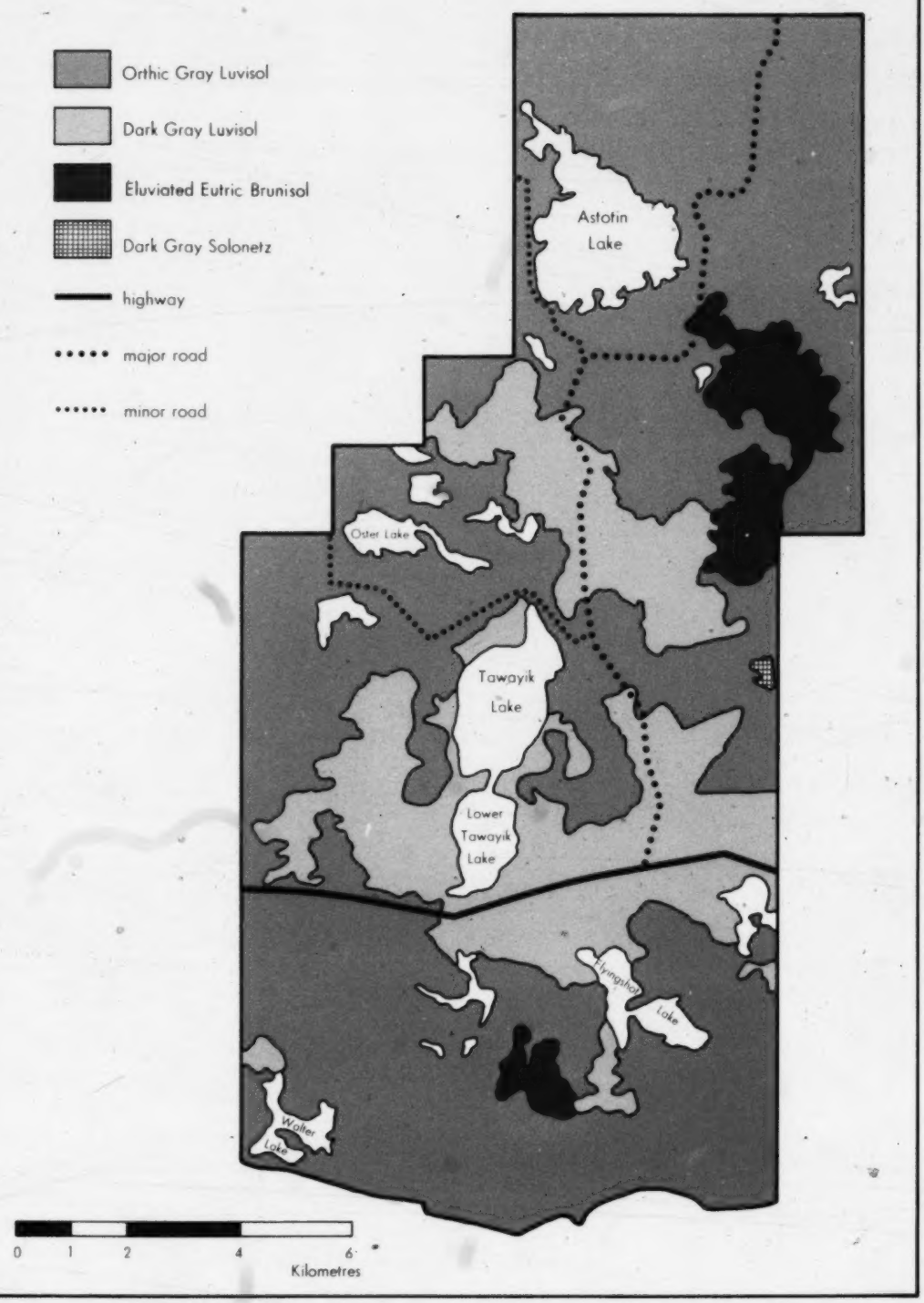
1.2.4 Soils

Soil genesis will reflect the interaction of, and local variations in, the basic soil forming factors. Crown (1977) suggested that differences in parent material, topography, aspect and drainage, as well as temporal changes in climate and vegetation have influenced soil development in the study area. The dominant soils of Elk Island National Park are Orthic Gray Luvisols (Figure 1.2) which have developed on the fine-grained till or loess deposits, under stands of aspen poplar (Crown, 1977). A strongly developed Bt horizon and leached acidic Ae horizon characterize this group. Other members of the Luvisolic Order are present, with Dark Gray Luvisols having formed primarily on lower relief, glaciolacustrine deposits. Occurrences of Brunisolic Order soils are confined to areas of deep sand deposits. Here, the low clay content of the parent material allows good development of the Ae horizon, with poor development of the Bt horizon. Solonetzic soils (Figure 1.2) are an isolated occurrence , found only at the *Soap Holes* (56°36'30" N 112°48'15" W). Situated in a groundwater discharge zone this area is permanently saturated. Salt precipitates result from the evaporation of the mineralized, discharging groundwater (Doherty, 1974).

1.3 General Geologic History

The present landscape is a cumulative product of geologic processes that operated during preglacial, glacial and postglacial times (Westgate *et al.*, 1976). The major geologic elements for the Edmonton district , and the study area specifically, are generalized as follows.

Figure 1.2 Generalized soil map, Elk Island National Park
(after Crown, 1977)



1.3.1 Preglacial

Bedrock Geology:

The bedrock of the study area (Figure 1.3) is mainly of Upper Cretaceous age (Carlson, 1967; Green, 1972). Composed of three weakly lithified sedimentary formations, it has a regional northwest–southeast strike and a shallow dip of only a few metres per kilometre to the southwest. The older strata of this sedimentary sequence are rocks of the Belly River Formation. These are composed of gray sandstones, clayey siltstones and mudstones with local ironstone beds. This formation is overlain by the marine and non–marine shales and clay–rich sandstones of the Bearpaw Formation. The youngest unit, the Edmonton Formation, accumulated in a non–marine environment and consists of bentonitic shales with lenticular sandstone layers and coal beds.

There is only one outcrop of bedrock within the study area (53°44'30" N 112°48'05" W) but this is outside the hummocky moraine limits. However, within the Cooking Lake moraine numerous outcrops of Cretaceous bedrock are found just north of Cooking Lake (Sections 3,8,9,10,15,16; Tp 52 Rg 21). Once thought to be *in situ*, and related to the Edmonton Formation, these are now known to be exposures of huge bedrock erratics which have been transported approximately 350 kilometres from the north–northeast. Microfloral analyses, carried out by C. Singh of the Alberta Research Council, on samples collected from these exposures, indicated erratics–derivation from the Grand Rapids Formation, the nearest outcrop of which is in the Fort McMurray area (Westgate *et al.*, 1976).

In Alberta, fluvial erosion of Tertiary, and possibly early Pleistocene age, was mainly responsible for the bedrock surface now masked by Quaternary deposits (Carlson, 1967). Preglacial topographic *highs* often coincide with contemporary uplands (Westgate, 1969). This appears to the case for at least the northern portion of Elk Island National Park. Near the northeastern corner of the park the contact between the Edmonton and Bearpaw Formations occurs. This is expressed by a distinctive escarpment trending northwest–southeast (Figure 1.4).

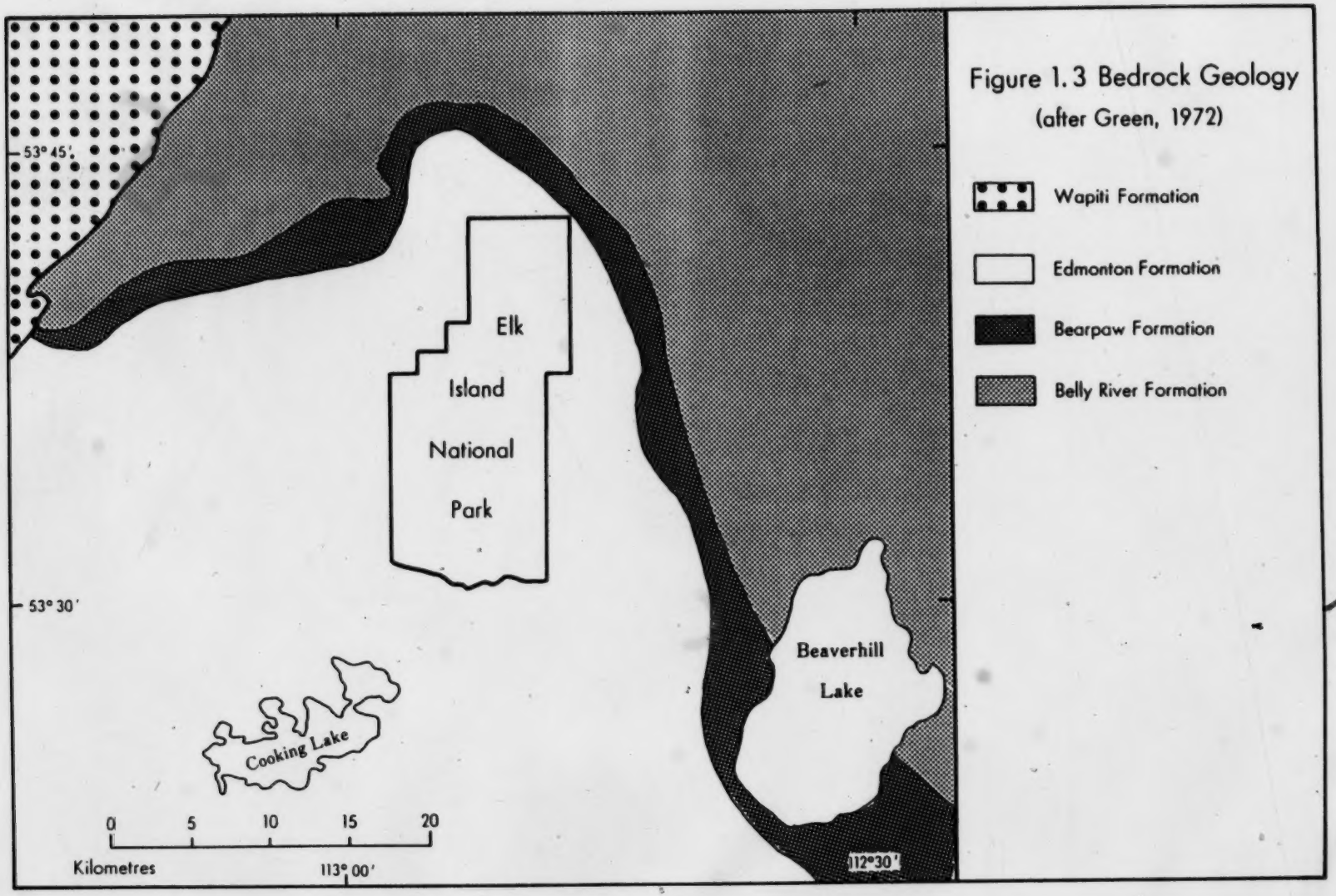


Figure 1.3 Bedrock Geology
(after Green, 1972)

COLOURED PICTURES
Images en couleur

Figure 1.4 The distinctive escarpment marking the contact of the Edmonton and Bearpaw Formations

The bedrock topography and preglacial drainage of the study area are generalized in Figure 1.5. Information on which this tentative map is based was acquired from three sources. R. Stein (personal communication, 1981) provided a preliminary bedrock topography map for NTS 83 H N.E. (scale 1:125,000). Because subsurface information was scant for Elk Island National Park, this was supplemented by data obtained from old water-well drilling reports (International Water Supply Ltd., 1961) and the author's own drilling programme. This map is only an approximation because more data would normally be required to accurately portray the bedrock surface.

Saskatchewan Gravels and Sands:

Alluvial gravels and sands of Cordilleran provenance, and preglacial age, are partly preserved as high-level upland *caps* , intermediate-level terrace sediments and low-level channel-fill deposits within preglacial valleys of Alberta. These are variously referred to as *Saskatchewan gravels and sands* (Warren, 1954; Stalker, 1968; Kathol and McPherson, 1975), *Saskatchewan Sands and Gravels* (Bayrock and Hughes, 1962) and *Saskatchewan Gravels* (Westgate, 1969; Westgate *et al.*, 1976). The *cap* deposits are probably of Late Tertiary age (Westgate, 1969; Kathol and McPherson, 1975) whereas the deposits within the preglacial valleys are more likely to be of Quaternary age. These preglacial sediments are composed mainly of quartzites and black chert with minor amounts of arkose, petrified wood, coal and clay ironstone (Kathol and McPherson, 1975). As such they are easily differentiated from younger, glaciofluvial and alluvial deposits which contain reincorporated igneous and metamorphic rocks of Canadian Shield provenance.

1.3.2 Glacial

The landform assemblages displayed within the study area and its surroundings are largely the product of the Laurentide ice sheet. Within the Edmonton district the sedimentary characteristics and stratigraphy of the Pleistocene deposits have been documented during the last three decades (e.g. Warren, 1954; Bayrock and Hughes, 1962; Bayrock and Berg, 1966; Rains, 1969; Westgate, 1969; Kathol and McPherson, 1975; Westgate *et al.*, 1976; Emerson, 1977; May and Thomson, 1978; Shaw, 1982). Interpretation of the stratigraphic succession has undergone many changes as different

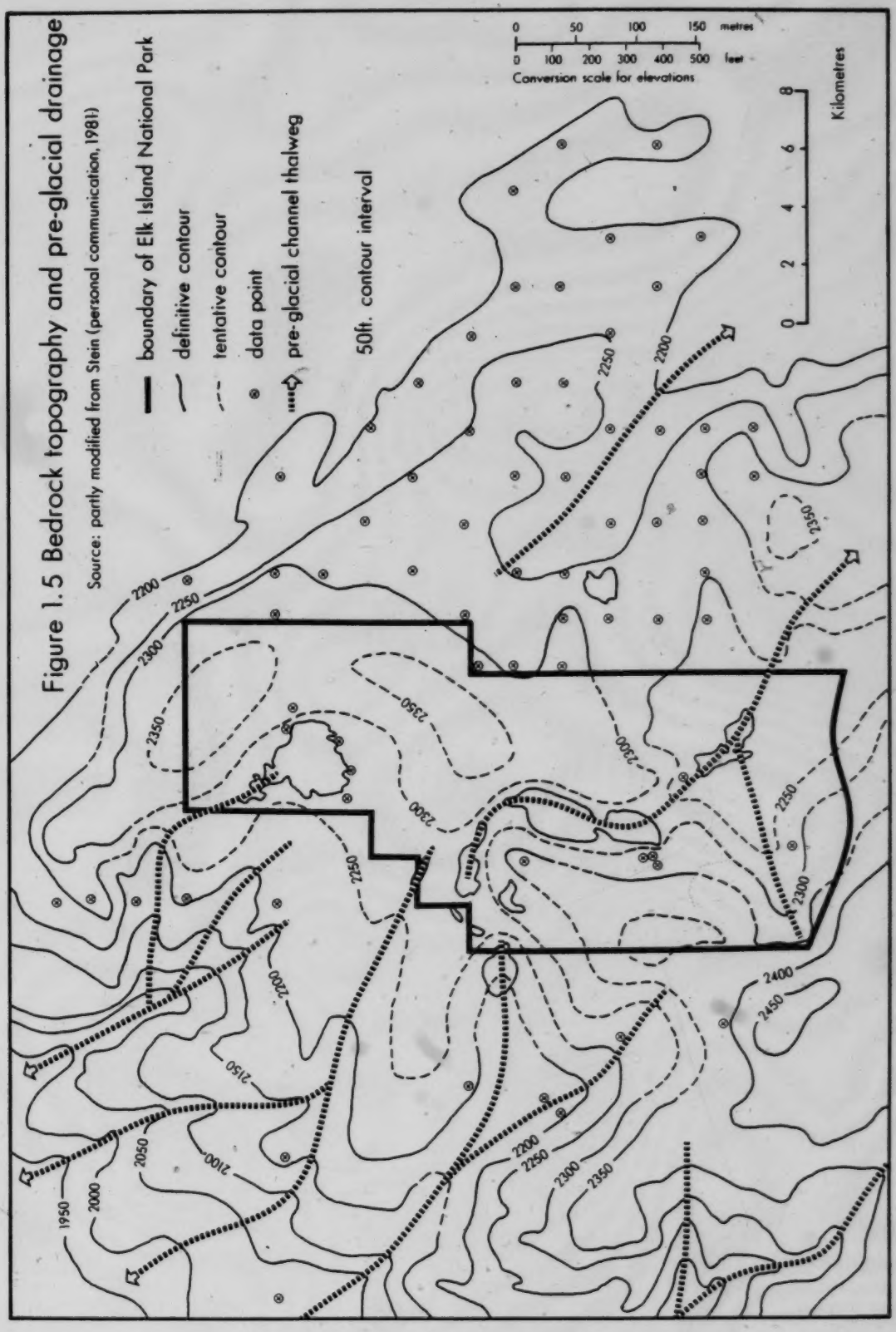


Figure 1.5 Bedrock topography and pre-glacial drainage
Source: partly modified from Stein (personal communication, 1981)
boundary of Elk Island National Park
definitive contour
tentative contour
data point
pre-glacial channel thalweg
50ft. contour interval
0 50 100 150 metres
0 100 200 300 400 500 feet
Conversion scale for elevations
0 2 4 6 8
Kilometres
1950
2000
2050
2100
2150
2200
2250
2300
2350
2400
2450

workers found new and partly conflicting information. In general, the succession has included till units resting upon bedrock or preglacial gravels and sands. The tills are often overlain by lacustrine sediments. The first, detailed, local maps on the distribution of Quaternary landforms and deposits were completed by Bayrock and Hughes (1962). The most recent map of the surficial geology for the Edmonton district (NTS 83H) was completed by the Alberta Research Council (Bayrock, 1972).

Tills:

Despite numerous field and laboratory investigations of the local tills and stratigraphic units, the question regarding the number of distinct episodes of glacial activity remains unresolved. Warren (1954) and Westgate (1969) described Tofield Sands, stratified quartzose sands up to 13 metres thick, in places separating two tills, a lower greyish till and an upper brown till. Bayrock and Hughes (1962) and Bayrock and Berg (1966) confirmed the till colour difference but attributed this to the oxidation of the upper 3 to 9 metres of till. They suggested that the boundary between oxidized and non-oxidized till was **not** related to a change in composition. Bayrock and Berg (1966), in an analysis of drill-hole and well-log records, noted the common occurrences of sands in the till, but in thicknesses usually less than 0.3 metres. They suggested that these were sand lenses representing "minor washing of glacial debris by running water" (Bayrock and Berg, 1966, p.9). Kathol and McPherson (1975, p.32), in agreement with Bayrock and Hughes (1962) and Bayrock and Berg (1966), stated "... till deposits are considered a single unit which often contain lenses of glaciofluvial sediments". May and Thomson (1978) also suggested that the frequent occurrence of sands intercalated with till represented *in situ* syndeposition, or proglacial deposition and associated burial by flow till. Shaw (1982) for the *Huggett* section, interpreted the sands between the two tills to be glaciofluvial since they showed sedimentary structures produced by relatively strong currents. These intervening sands could represent outwash deposited during the retreat of ice of the first advance or during the second advance, or both (Shaw, 1982). The discontinuous nature of the so-called Tofield Sands has led to some confusion. As is presented above, some authors have attributed sand units to melt-out of a single till whereas others have interpreted them as separating two tills.

Analyses of the mechanical composition of the different coloured till units in the Edmonton area have shown that the lower unit consistently has a higher clay content than the upper unit (Table 1.1). In addition, the structures of these tills often differ dramatically . The upper till tends to be dense and massive with good columnar joint structure but poor secondary fracturing. Conversely, the lower clay-rich till often possesses a highly fractured, blocky structure (Rains, 1969; Westgate *et al.*, 1976).

In the Cooking Lake moraine two tills have been differentiated on the basis of colour and structure (Emerson, 1977). Of interest are the stratigraphic occurrences and clay mineralogy of the so-called *pink unit* , a weathered horizon of the lower till (Westgate *et al.*, 1976; Emerson, 1977). This *pink unit* is occasionally preserved as lenses in the upper till, possibly indicating incorporation during a second phase of glacial activity (Emerson, 1977).

However, the differentiation of the two tills is further complicated when the regional ice flow direction, for each of the two presumed episodes, is reconstructed. A northeast-southwest flow direction for the last episode of glacial activity has been interpreted from indicators such as till fabric analyses (Rains, 1967, 1969; Westgate, 1969; Ramsden, 1970; Ramsden and Westgate, 1971; Westgate *et al.*, 1976; Shaw, 1982), sole markings (Westgate, 1968, 1969; Westgate *et al.*, 1976; Shaw, 1982; Welch, 1983), plus the alignment of nearby streamlined landforms (Gravenor and Meneley, 1958; Gravenor and Bayrock, 1961; Bayrock and Hughes, 1962; Bayrock and Berg, 1966; Westgate, 1968, 1969; Bayrock, 1972; Westgate *et al.*, 1976). Figure 1.6 illustrates much of this evidence.

The regional ice flow direction for the first glacial episode is speculative. Till fabric analyses of the lower till unit at selected locations within the Edmonton area have yielded conflicting results (Figure 1.7). Rains (1967) found an east-west alignment of till pebbles at one location but a well defined northeast-southwest preferred orientation in the Whitemud Creek valley area (Rains, 1969). Westgate *et al.*, (1976), although not confident that both till units were represented, stated that colour differences suggested two till units were exposed at the *Big Bend* section on the north bank of the North

LOCATION	REFERENCE	NUMBER OF SAMPLES	TILL UNIT	PERCENTAGE COMPOSITION		
				sand	silt	clay
Edmonton area	Bayrock and Hughes, 1962	14	unknown	41.1	31.4	27.5
Edmonton city	Bayrock and Berg, 1966	6	unknown	44.0	26.0	30.0
Kropp and Brettville gravel pits, east of Edmonton city	Rains, 1967	4	upper	38.1	30.4	31.5
		1	lower	21.9	29.1	49.0
Whitemud Creek valley	Rains, 1969	4	upper	37.9	39.3	22.8
		10	lower	34.2	30.8	34.9
Edmonton area	Westgate, 1969	7	upper	44.0	36.0	20.0
		9	lower	43.0	30.0	27.0

Table 1.1 Mean mechanical composition of Edmonton area tills

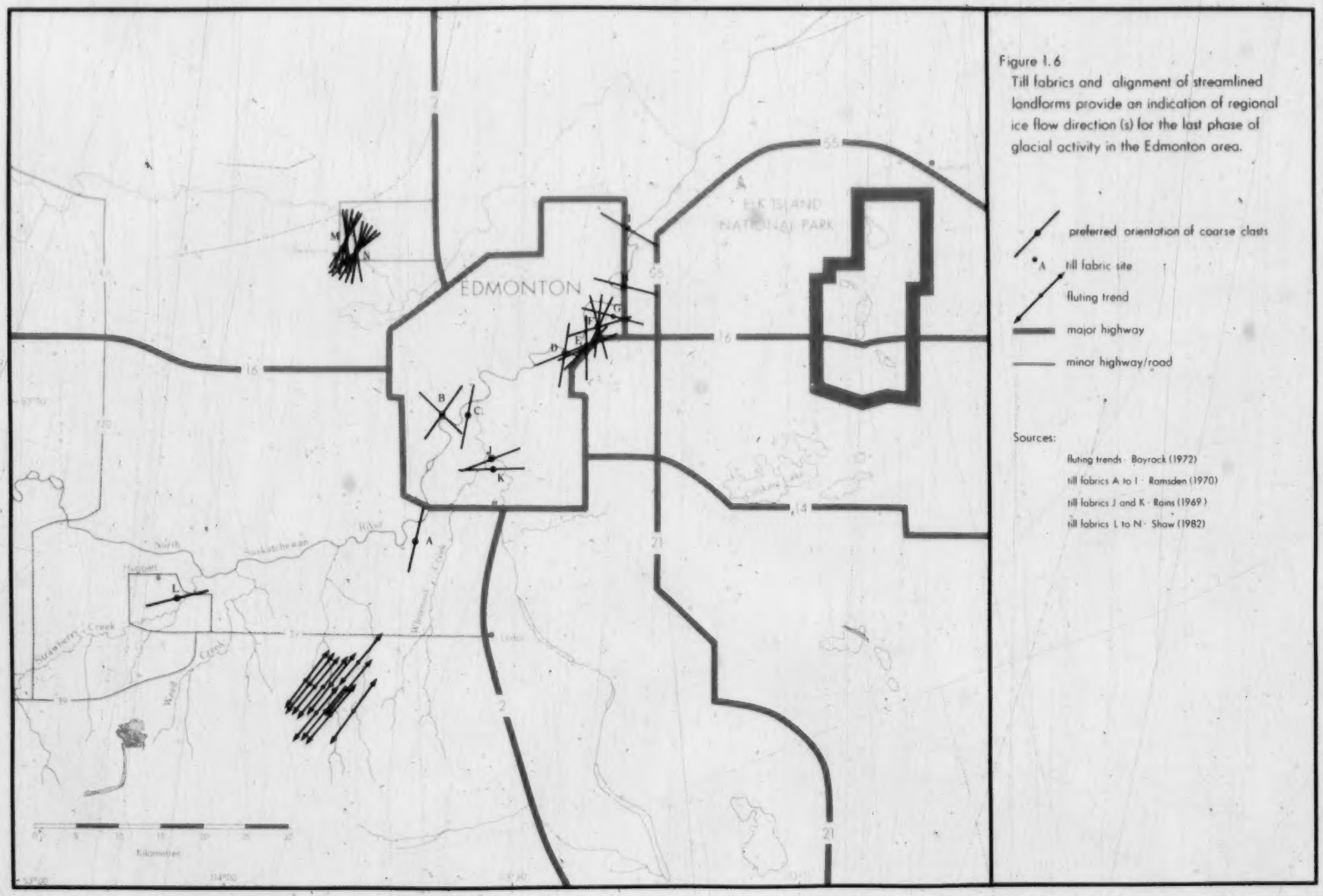


Figure 1.6
Till fabrics and alignment of streamlined landforms provide an indication of regional ice flow direction (s) for the last phase of glacial activity in the Edmonton area.

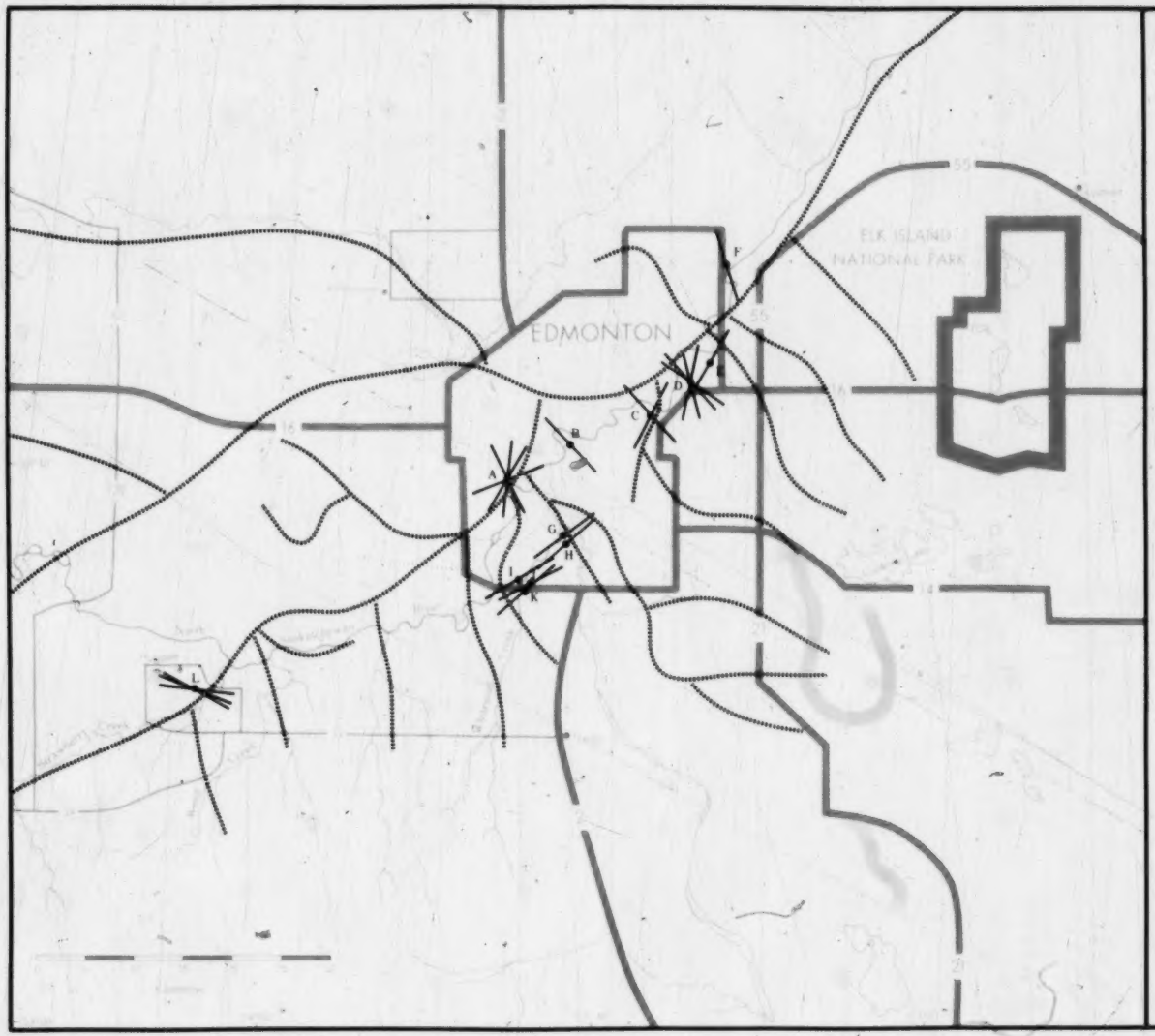


Figure 1.7
Conflicting till fabric results for the first phase of glacial activity in the Edmonton area. The thalwegs of the pre-glacial drainage may have strongly influenced local ice flow directions and/or till depositional processes.

preferred orientation of coarse clasts

B till fabric site

pre-glacial channel thalweg

major highway

minor highway/road

Sources:

pre-glacial channel thalwegs - Carlson (1967)

till fabrics A to F - Ramsden (1970)

till fabrics G to K - Rains (1969)

till fabric L - Shaw (1982)

Saskatchewan River in Edmonton. Till fabric analyses from five sites in vertical succession at the section all revealed a northeast–southwest direction (Table 1.2). Westgate (1969), Ramsden (1970), Ramsden and Westgate (1971) and Shaw (1982) generally noted a northwest–southeast preferred orientation of coarse clasts within the lower till.

These conflicting till fabric results are not surprising when the wide variability of factors which influence pebble orientation in till are considered. Preferred coarse clast alignment may reflect ice flow direction in a *loose* statistical sense only. Confidence in till fabric analysis is increased with the knowledge of the type of till, and thereby the processes which led to its deposition. However, for the Edmonton area little is known about the till types represented. Only Shaw (1982) defined the till types in which he measured the coarse clast orientations. Further, both parallel and transverse till fabrics have been noted for lodgement and melt–out tills elsewhere. Pebble alignment in *flow* till usually reflects the direction of debris flow which is often independent of ice flow direction.

The preglacial topography also may have influenced local ice flow directions and/or till depositional processes. In the Edmonton area many of the contemporary river and stream channels follow, for at least part of their length, the preglacial valley thalwegs. It is from exposures in these contemporary fluvial valleys that most of the till fabrics have been taken. For example, Ramsden (1970) collected till fabric information at several locations along the contemporary North Saskatchewan River valley. Although the river has cut a *new* postglacial valley along this reach, the local response of the Laurentide ice sheet to the large preglacial Beverly Valley, just to the north, is unknown. Ramsden (1970) suggested that, particularly at two locations (A and C, Figure 1.7), the ice flow was probably altered by such preglacial valleys.

Another complication is that the pebble fabric of the lower till may have been altered by later overriding ice at several locations. Ramsden (1970, p. 145) suggested that differentiation of primary fabrics and those which may have undergone reorientation was the "biggest problem in interpreting lower till fabrics in the Edmonton area".

Distance of sampled unit below top of till (feet)	Colour (Munsell designations)	Texture sand (%)	silt (%)	clay (%)	Till fabric azimuth of dominant mode of pebble fraction (degrees from true north)
0 - 5	5Y 7/2	48	34	18	35
5 - 10	2.5Y 5/4	40	34	26	30
10 - 15	10Y 7/3	40	36	24	10
15 - 20	2.5Y 5/2	35	35	30	50
35 - 55	10Y 5/3	38	43	19	20

Table 1.2 Colour, texture and fabric of till at the "Big Bend" Section

(after Westgate et al., 1976)

Another problem is that often the differentiation of *upper* and *lower* tills is ambiguous. The till fabrics depicted in Figures 1.6 and 1.7 are taken directly from each of the cited works and therefore reflect each investigator's recognition of the two tills. Given the tremendous problems of field differentiation between the *upper* and *lower* tills, it is reasonable to suggest that in some cases fabrics were measured in an incorrectly identified till.

Finally, the ice sheet, or a lobe of it, may indeed have advanced into the area from the northwest (Dyke *et al.*, 1982). Considering that the preglacial drainage gradient was to the northeast, the ice sheet would have had to continually *climb* this while it advanced into western Canada. A possible alternative to the presumed northeast–southwest flow direction is that the ice sheet accumulated in the central region of Keewatin, then flowed more or less west, finally advancing southward into central Alberta. Additional, although debatable, evidence for this northwest–southeast flow direction possibility is available. During a recent drilling programme by the Alberta Research Council just east of Holden, Alberta, an erratic block of oil sands, resting directly on bedrock and overlain by till, was encountered in a low ridge. Subsequent analyses of the mineral content indicated derivation of this erratic from the Wabasca Oil Sands which are only known to outcrop NNW of the drilling site (Andriashek, personal communication, 1982).

The regional evidence, although inconclusive, favours the existence of at least two distinct Pleistocene tills at some localities within the Edmonton area. The two tills are here assumed to represent two episodes of glacial activity, not necessarily of full glaciation extent.

Glaciolacustrine Sediments:

In the Edmonton district widespread glaciolacustrine sediments occur at or near the surface (Bayrock, 1972). As the present drainage direction in much of Alberta is northeasterly, the last ice sheet retreated in this same direction (Bayrock and Hughes, 1962). The physiography, and mode of ice sheet recession, therefore were conducive to the formation of proglacial lakes which were impounded in front of the Laurentide ice sheet margin. Retreat of the ice sheet allowed these lakes to drain episodically (Bayrock

and Hughes, 1962). The sequence of formation and drainage of these proglacial lakes in Alberta and Saskatchewan has been well documented by St. Onge (1972; 1980) and Christiansen (1979).

One of these proglacial lakes is here referred to as Glacial Lake Edmonton. Some problem has arisen in terminology for this major proglacial lake because at least two stages have been recognized. Hughes (1958) and Bayrock and Hughes (1962) included both stages as Glacial Lake Edmonton. The first stage started when the wasting continental ice had receded far enough to permit deposition of the lowermost lacustrine materials in the area. At this stage the glacial margin to the east and north, and the higher land to the west and south, confined the lake. Although most land covered by Glacial Lake Edmonton was probably completely deglaciated as the lake became established, some peripheral portions of the lake probably transgressed over buried ice (Bayrock and Hughes, 1962). Deltas were built into this lake at a number of locations around the ice edge. Because much of this deltaic sedimentation took place over or around ice, many of the relict delta surfaces are now pitted (Bayrock and Hughes, 1962). As the lake level rose the basin of Glacial Lake Edmonton filled until an outlet was found. Most of the lake water was eventually drained southeast to the Battle River system via the Gwynne Outlet (Hughes, 1958; Bayrock and Hughes, 1962). Hughes (1958) suggested that as water escaped the outlet floor was deepened from an elevation of approximately 2425 feet (739 metres) to 2265 feet (690 metres).

The second stage of Glacial Lake Edmonton thus began and continued until further wasting of the ice to the northeast permitted complete drainage by the North Saskatchewan River. St. Onge (1972) renamed these stages as, first, Glacial Lake Leduc and second, Glacial Lake St. Albert.

As the Laurentide ice sheet retreated further, the lower land near Bruderheim was inundated by meltwater. Glacial Lake Bruderheim (St. Onge, 1972) was bounded to the north and east by the ice mass and, to the south, by stagnant ice and debris in the present study area. The water and sediment supplied to the lake were largely from Laurentide drainage, but also from the northeastward flowing North Saskatchewan River which constructed a lower delta into the lake. The elevation of Glacial Lake Bruderheim was

estimated to be between 2150 feet (655 metres) and 2075 feet (632 metres). Eventually, this lake was emptied southeastward via the Vermilion River Channel (St. Onge, 1972; Christiansen, 1979).

The radiocarbon ages of the glacial lake sediments have not been established. Only from relative and regional extrapolation can *estimates* be placed on the time period in which Glacial Lake Edmonton and Glacial Lake Bruderheim existed. Christiansen (1979) proposed a deglaciation chronology for Saskatchewan. Although he made no attempt to extrapolate his work far into Alberta it was later suggested by St. Onge (1980) that at least four of Christiansen's (1979) phases were completely contiguous with those of his earlier work (St. Onge, 1972). Therefore, Christiansen's phase 4 (14,000 yrs. B.P.), phase 5 (12,500 yrs. B.P.) and phase 6 (12,000 yrs. B.P.) are considered to be approximately time-synchronous with phase 4 (Glacial Lake Leduc), phase 5 (Glacial Lake St. Albert) and phase 6 (Glacial Lake Bruderheim), respectively, from the work of St. Onge (1972).

1.3.3 Postglacial

The interpretation of postglacial palaeoenvironments in Alberta has been made by a number of researchers. The techniques employed include pollen analysis (Hansen, 1949; Lichti-Federovich, 1970; Ritchie, 1976; Emerson, 1977; Forbes and Hickman, 1978, 1981; Hickman *et al.*, 1978; Hickman and Klarer, 1981; Schweger *et al.*, 1981; Vance *et al.*, 1983), tephrachronology (Westgate *et al.*, 1976; Waters, 1979), paleosol identification (Waters, 1979), radiocarbon dating of freshwater molluscs and analysis of their climatic preferences (Harris and Pip, 1973; Emerson, 1983) plus oxygen isotope studies of molluscs (Fritz and Krouse, 1973; Emerson, 1977). The results of these studies suggest that a relatively warm and dry climate existed in Alberta from approximately of 8,500 to 6,600 yrs. BP (Waters, 1979). This period is known as the Altithermal interval (Table 1.3).

Shells extracted from superglacial lake sediments radiocarbon dated at 10,880 +155 yrs. BP [I-8484] and 9,050 +150 yrs. BP [I-4552] (Emerson, 1977). Oxygen isotope analyses on these shell samples and others extracted from Wabamun Lake sediments (Fritz and Krouse, 1973) indicate a period of high evaporation, possibly the

REFERENCE	STUDY LOCATION	INVESTIGATIVE TECHNIQUES
Lichti - Federovich (1970)	Lofty Lake, Alberta	Pollen stratigraphy
Harris and Pip (1973)	Alberta	Radiocarbon dating and climatic preference of molluscs
Fritz and Krouse (1973)	Lake Wabamun, Alberta	Oxygen isotope analysis of molluscs
Ritchie (1976)	Western Canada	Pollen stratigraphy and radiocarbon dating of organics
Hickman and Klarer (1981)	Lake Isle, Alberta	Pollen stratigraphy and sediment chemistry
Schweger et al.,(1981)	Central Alberta	Pollen stratigraphy
Vance et al.,(1983)	Smallboy Lake, Alberta	Pollen stratigraphy

GENERAL INTERPRETATIONS

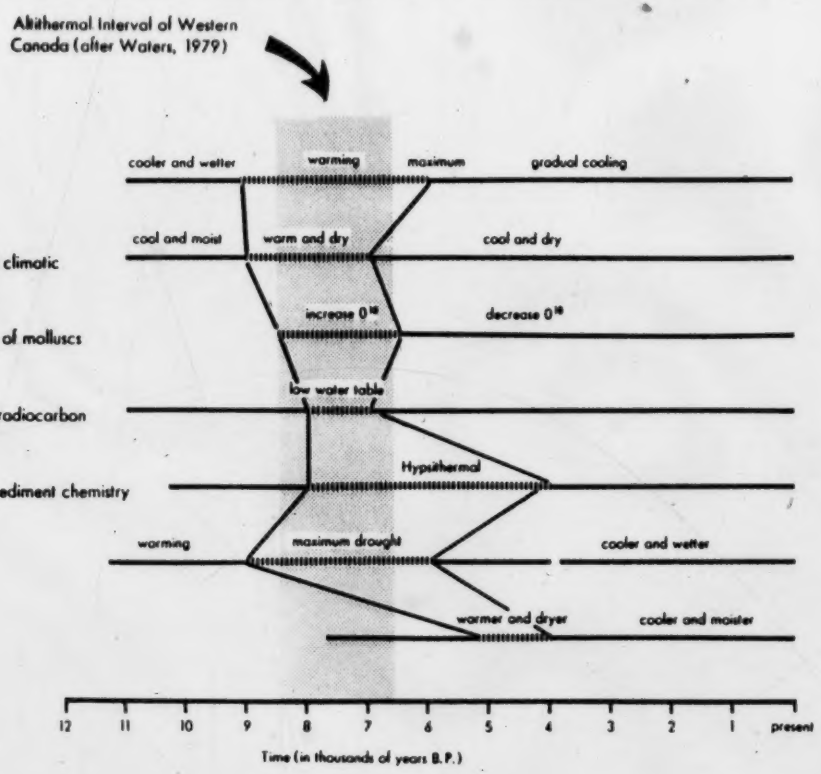


Table 1.3 Interpretation of post-glacial palaeoclimates in Alberta

result of a drier climate. A second peak in O^{18} values occurred between 8,500 and 6,500 yrs. BP (Fritz and Krouse, 1973). This second peak fits more closely with the Altithermal interval (Table 1.3). The deposition of Mazama Ash (*circa* 6,600 yrs. BP) appears to roughly coincide with the end of the Altithermal interval. At this time grasslands began to be partially displaced by boreal forest vegetation.

Various basal dates from lake sediment cores (Figure 1.8; Table 1.4) indicate that at least some central Alberta lakes occupied their present basins between about 7,380 +245 yrs. BP [I-7154] and 3,970 +170 yrs. BP [DIC-627] (Waters, 1979). It is quite possible that even some of the larger lakes of the study area came into existence as late as 6,000 yrs. BP (C. Schweger, personal communication, 1981).

Partly as a result of wind erosion of former glaciolacustrine deposits a variable thickness of fine-grained aeolian sands and silts mantles parts of the study area (Figures 1.9 and 1.10). Emerson (1977) used a scanning electron microscope to study the surface texture of fine sand grains sampled within Elk Island National Park . The grains appeared to be much smoother than those transported by water and were classified as aeolian. Following the drainage of local proglacial lakes, and the termination of glacial outwash, winds were presented with substantial sources of previously sorted, poorly stabilized, fine sediments. Deposition in the form of dunes and thin loess sheets ensued. The orientation of longitudinal and parabolic dunes led Odynsky (1958) to state that the effective wind direction, during their formation, must have been from the northwest in the Edmonton area. Westgate (1969) maintained that dunes near Duffield, west of Edmonton, were formed in two distinct phases separated by a stable period when soil developed. A Mazama Ash marker bed (*circa* 6,600 yrs. BP) was identified from one of the palesols. Therefore the first phase of dune formation must have begun after the drainage of Glacial Lake Edmonton and probably extended into the Altithermal interval. The age of the second phase of dune formation is unknown.

Emerson (1977) noted that at some locations in the study area aeolian sands were mixed with alluvial sands in superglacial lacustrine complexes. This observation, and the presence of loess mantling the hummocks in which these lacustrine sediments were found, indicates that aeolian deposition started prior to the removal of buried ice and

NAME	LOCATION (Lat. N)	(Long. W)	RADIOCARBON DATE (Years B.P.)	CORE DEPTH (cm)	REFERENCE
Lofty Lake	54° 44'	112° 29'	11,400 ± 190 [GSC-1049]	549-554	Lichti-Federovich (1970)
Moore Lake	54° 30'	110° 32'	11,300 ± 170		Schweger et al.,(1981)
Alpen Siding	54° 27'	113° 00'	10,700 ± 170 [GSC-1093]	380-385	Lichti-Federovich (1972)
Lake Isle	53° 37'	114° 45'	9,530 ± 120 (10,300 *)	603-613 (655)	Hickman and Klarer (1981)
Smallboy Lake	53° 35'	114° 08'	7,380 ± 245 [I-7154]	443-450	Vance et al.,(1983)
Joseph Lake	53° 25'	113° 55'	7,035 ± 105 [S-2087]	-	Vance et al.,(1983)
Muskrat Bog	53° 22'	114° 33'	6,240 ± 175	934	Schweger (personal communication, 1981)
North Hastings Lake	53° 26'	112° 53'	6,180	350	Waters (1979)
Lac. Ste. Anne	53° 42'	114° 21'	5,630 ± 125	184	Forbes and Hickman (1978, 1981)
Hastings Lake	53° 30'	113° 00'	4,780 ± 80	386	Forbes and Hickman (1981)
Hastings Lake	53° 30'	113° 00'	4,580 ± 190 [DIC-629]	345	Forbes and Hickman (1981)
Baptiste Lake	54° 45'	113° 34'	3,760 ± 145 (4,600 *)	659-664 (802)	Hickman et al.,(1978)
Bog (Elk Island National Park)	53° 39'	112° 52'	4,180 ± 70	233-240	Vance (1979)
Bog near Fort Saskatchewan	53° 48'	113° 05'	4,030 ± 60 [Beta-2626]	-	Vance et al.,(1983)
Pond (Elk Island National Park)	53° 38'	112° 51'	3,970 ± 170 [DIC-627]	165-170	Vance et al.,(1983)

* extrapolated basal date

Table 1.4 Basal dates from lake and bog sediment cores, central Alberta

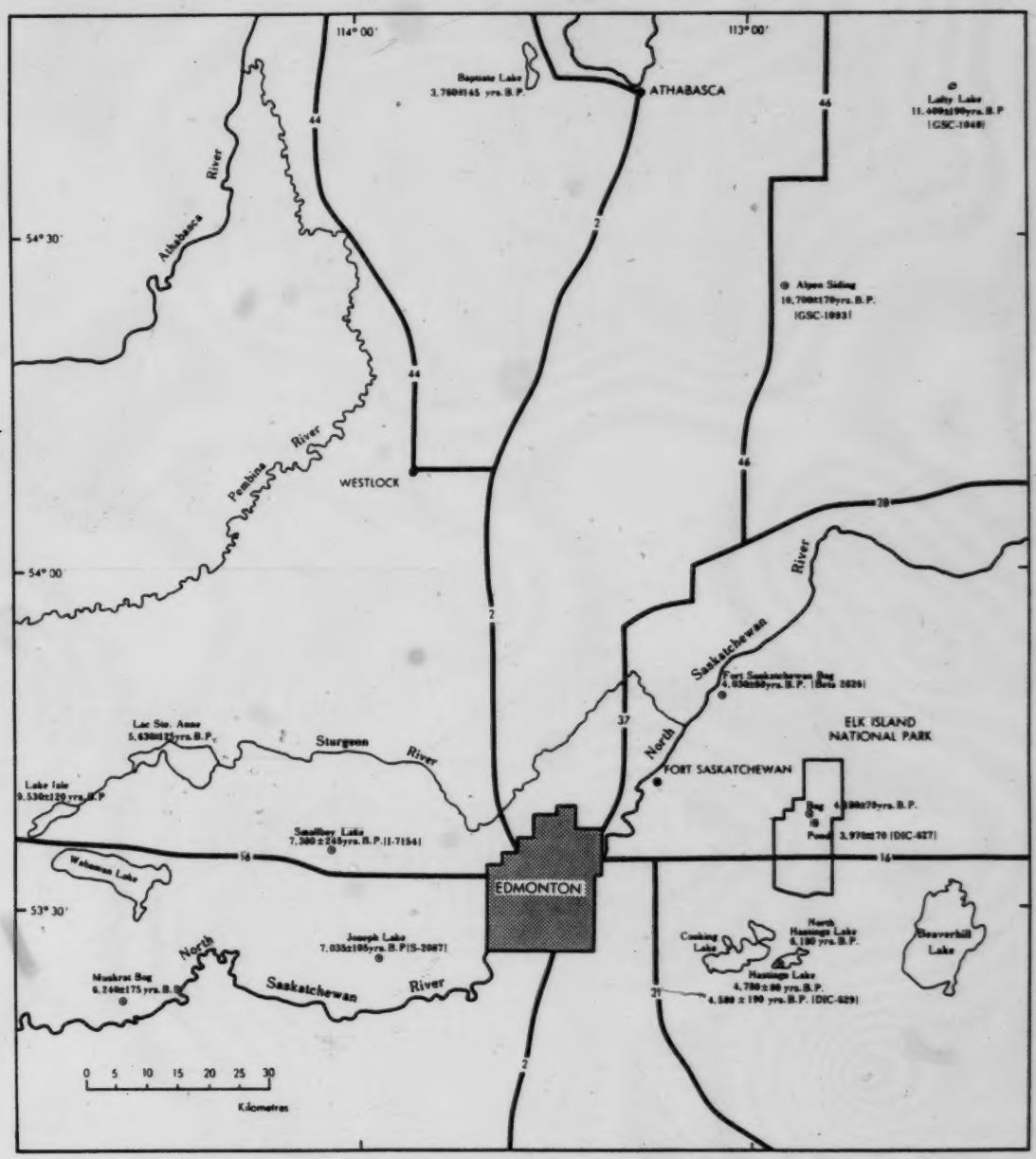


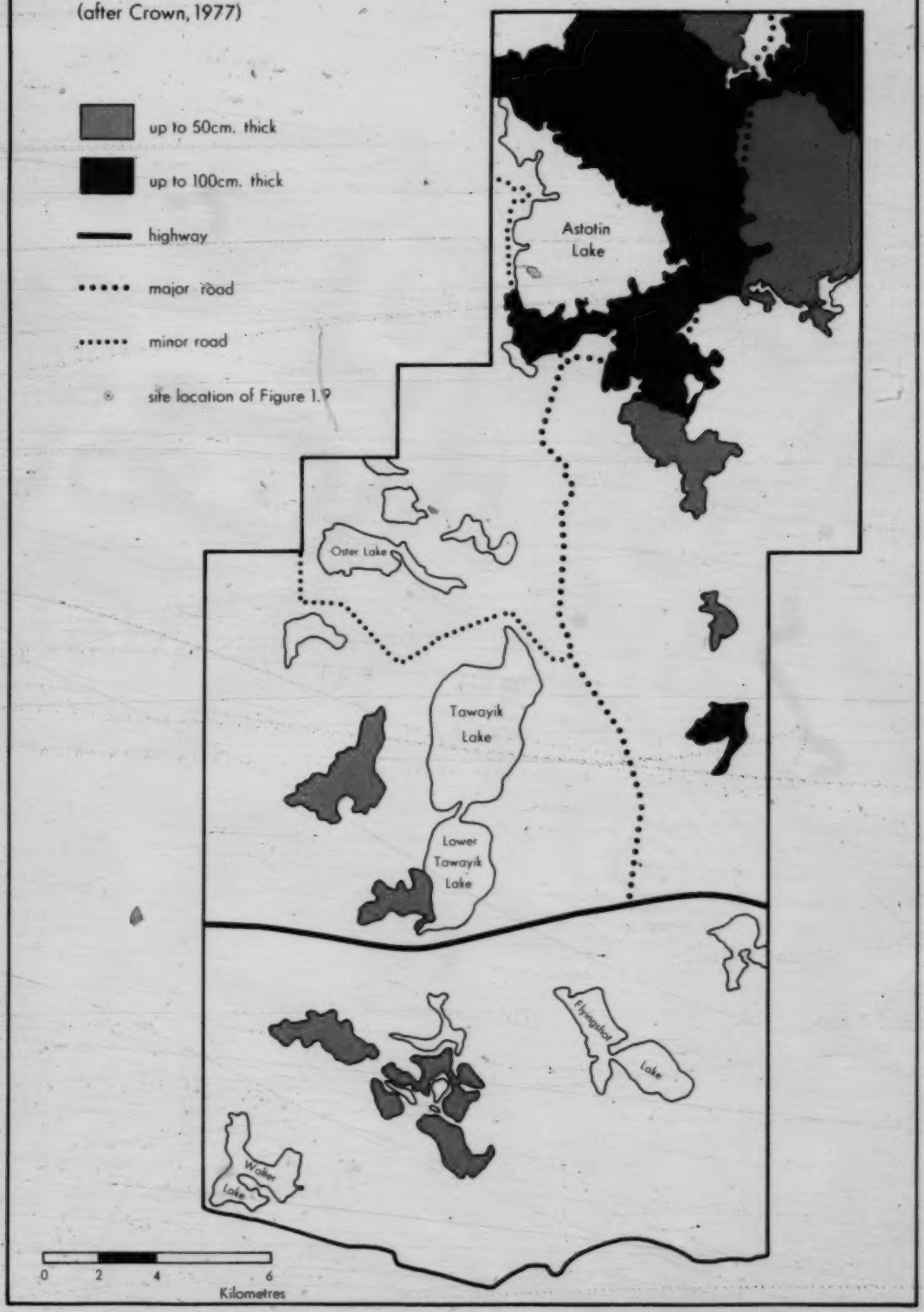
Figure 1.8 Sites of basal dates for lake and bog sediments in central Alberta

(see Table 1.4 for sources)

COLOURED PICTURES
Images en couleur

Figure 1.9 A veneer of aeolian deposits resting directly on till in the study area. (refer to Figure 1.10 for site location)

Figure 1.10 The distribution of aeolian sediments, Elk Island National Park
(after Crown, 1977)



continued after the final configurations of the landforms were established. The period of loess deposition could possibly have extended to the end of the Altithermal interval, although no fixed date can be firmly established.

2. GLACIGENIC SEDIMENT PROPERTIES, THEIR FIELD RECOGNITION AND DESCRIPTION

2.1 Introduction

Field investigations in geomorphology are largely founded upon observation and inference. Only attributes which are surficial can be observed, all else must be inferred. Inferences are made by interpreting combinations of the visible properties. In this chapter attributes which are diagnostic of selected, relevant deposits are reviewed. Finally the descriptive methods used to investigate these diagnostic attributes are discussed at some length.

Sites were selected for field investigation and sampling laboratory analyses based on aerial photograph interpretation and a reconnaissance of the field area. These sites were selected on the basis of their accessibility; or their representation of *problem areas* or typical terrain (displaying widespread topographic qualities). Exposures along road cuts and in other man-made excavations provided most information on the the surficial deposits. However, where good sections were lacking, or where existing sections were not sufficiently deep, sample sites were excavated by a backhoe whereas others were drilled.

2.1.1 Preliminary Aerial Photograph Interpretation

Aerial photograph interpretation was of primary importance in the study of landform associations within the field area. Preliminary ideas were recorded when these landform assemblages were viewed at various scales of photography. Often landforms which are not easily recognized on the ground are well portrayed on aerial photographs and their shapes, limits and associations with the surrounding landscape may be distinguished. Vegetation patterns are well displayed on the aerial photographs and, in turn, these offer clues as to the nature of the underlying surficial materials.

Numerous types and scales of aerial photographs were available for Elk Island National Park and the surrounding area. Parks Canada provided true colour photographs at a scale of 1:15,840 while various scales of black and white panchromatic images were

also available. The aerial photographs were viewed in the laboratory and the interpreted information was traced onto acetate overlays. A composite of these overlays was set up to produce an uncontrolled mosaic of the study area. In this manner a preliminary map of the surficial geology and landform associations was produced.

2.1.2 Drilling

Two drilling programmes were undertaken within the study area. In the first a large *Bratt-22* rotary drill rig, under contract from Canadian Geological Drilling, was used. A portable *Minuteman* auger obtained from the Northern Forest Research Station, Edmonton, was employed in the second programme. Although the capabilities and limitations of the two rigs differed greatly the dry-auger drilling and sample collection procedures were essentially the same for both.

Once the rigs were positioned hollow augers were affixed. Six inch diameter, five foot length augers were used for the large rig whereas the portable rig required three inch diameter, three foot augers. *Break points* provided markers for drilling depth. One auger length was driven into the fresh overburden at a time. Once the full depth of this auger was inserted it was immediately pulled out for analysis of the core. The surface debris on the sampling auger was first removed. This was essential to ensure that the fresh sample was not contaminated with material scraped from the sides of the hole as the augers were removed. Working down from the top of the auger the new sample was described according to its colour, weathering (unoxidized/oxidized), matrix texture (ternary system), moisture content (wet/dry), degree of consolidation (compact/friable), bedding character (apparent/not apparent), plus pebble content and their lithologies. At one metre intervals selected samples were peeled off the auger, trimmed, packaged in labelled polythene bags, and stored for laboratory tests. After each sample was logged and removed the auger was completely cleaned. Another auger length was added and the complete flight was passed down into the hole. This procedure was repeated for the full depth of the sample hole.

The value of drilling in studies such as this is currently debated. The biggest problem is the representativeness of only one six inch or three inch diameter core.

Another criticism is that sedimentary structures tend to be disturbed or destroyed by the auger. Although contorted on the drill auger, rudimentary bedding structures were recognizable. Another potential problem is sample contamination with material dragged from the walls of the borehole as the auger flight is removed. However, if proper measures are taken this method of exploration can provide useful reconnaissance results regardless of such problems.

2.1.3 Section Description

Section description followed an orderly procedure of observation, measurement, assessment and logging. Both the external qualities of the landform into which the section was cut and the internal sediment and structural characteristics were described. A general term characterizing the morphologic expression of the landform (hummock, ridge, plain) was assigned, while its association with neighbouring landforms was assessed and recorded. Other external qualities such as slope angles and, where applicable, orientation (ridge form) were measured. The basic sediment units were identified and a primary division into diamicton/till, glaciofluvial, or glaciolacustrine sediments was completed. Often lenses or blocks of stratified material occurred within a diamicton/till section. These were logically differentiated on the basis of their formation, i.e. whether by water or ice. The major units and their relationships within the section were sketched and photographed.

2.2 Diamicton/Till Sediment Properties

2.2.1 Definition

Till is the product of glacial sedimentation and has both sedimentologic and genetic connotations (Flint, 1971; Sugden and John, 1976). The term was first introduced, in the context of glacier dynamics, by Geikie (1863, p. 185) as:

> " a stiff clay full of stones varying in size up to boulders produced by abrasion carried on by the ice sheet as it moved over the land ".

Descriptive synonyms such as boulder–clay (Charlesworth, 1957) and moraine have since appeared but are either infrequently used or misused in the literature.

Boulder-clay has lost its popularity as a term because boulders and clay may not normally be the main constituents of till (Goldthwait, 1971). Moraine is now accepted as a morphologic term for an accumulation of glacigenic deposits (Sugden and John, 1976). Since its inception the definition of till has evolved because the complex sedimentological processes of glacial deposition, under various conditions, have become better understood. The definition has been *expanded by liberals* and *narrowed by conservatives*. Recently, Boulton (1976, p. 65) defined till as:

> " an aggregate whose components are brought together and deposited by the direct agency of glacier ice and which, although it may suffer post-depositional deformation by flow, does not undergo subsequent disaggregation and redeposition ".

Lawson (1979, p. 28) defined till more conservatively as:

> " sediment deposited directly from glacier ice which has not undergone subsequent disaggregation and resedimentation ".

The major difference between these definitions is the manner in which these two authors have dealt with deposits formed superglacially or proglacially. Very few problems are encountered within the definition for lodgement or melt-out till. However, in the superglacial and proglacial environments, where flow by gravity may redistribute the debris, problems arise in defining a *true* till. Is a true till one that maintains the inherent characteristics of the debris/ice source or can it be debris which has its source of ice but is redistributed superglacially (or proglacially) before it is deposited?

There is a problem in Boulton's (1976) definition as to what he considers redeposition. Is *flow till* merely a transition phase to final deposition where all buried ice has been removed and thus in its final configuration or is deposition merely release of debris from ice while stagnant buried ice persists? It is difficult to see why Boulton (1976) still includes flow till in his classification where there must have been some reorganization of material and loss of the characteristics inherited from a glacier. For this reason Lawson's (1979) definition is preferred by the author because he completely omits those sediments which, in the superglacial or proglacial environment, may flow by gravity. This redistribution process should result in resedimentation and therefore debris will inherit the characteristics of this transport and deposition, separately from that of the glacier ice. Lawson (1981) proposed that these sediments are in fact diamictons, not till,

insofar as they result from resedimentation processes subsequent to initial release from glacier ice. Goldthwait (1971, p. 5) perhaps best summarized the till definition problem with his statement "At least, everyone agrees that the word till does mean glacial handling".

2.2.2 Formation and Deposition

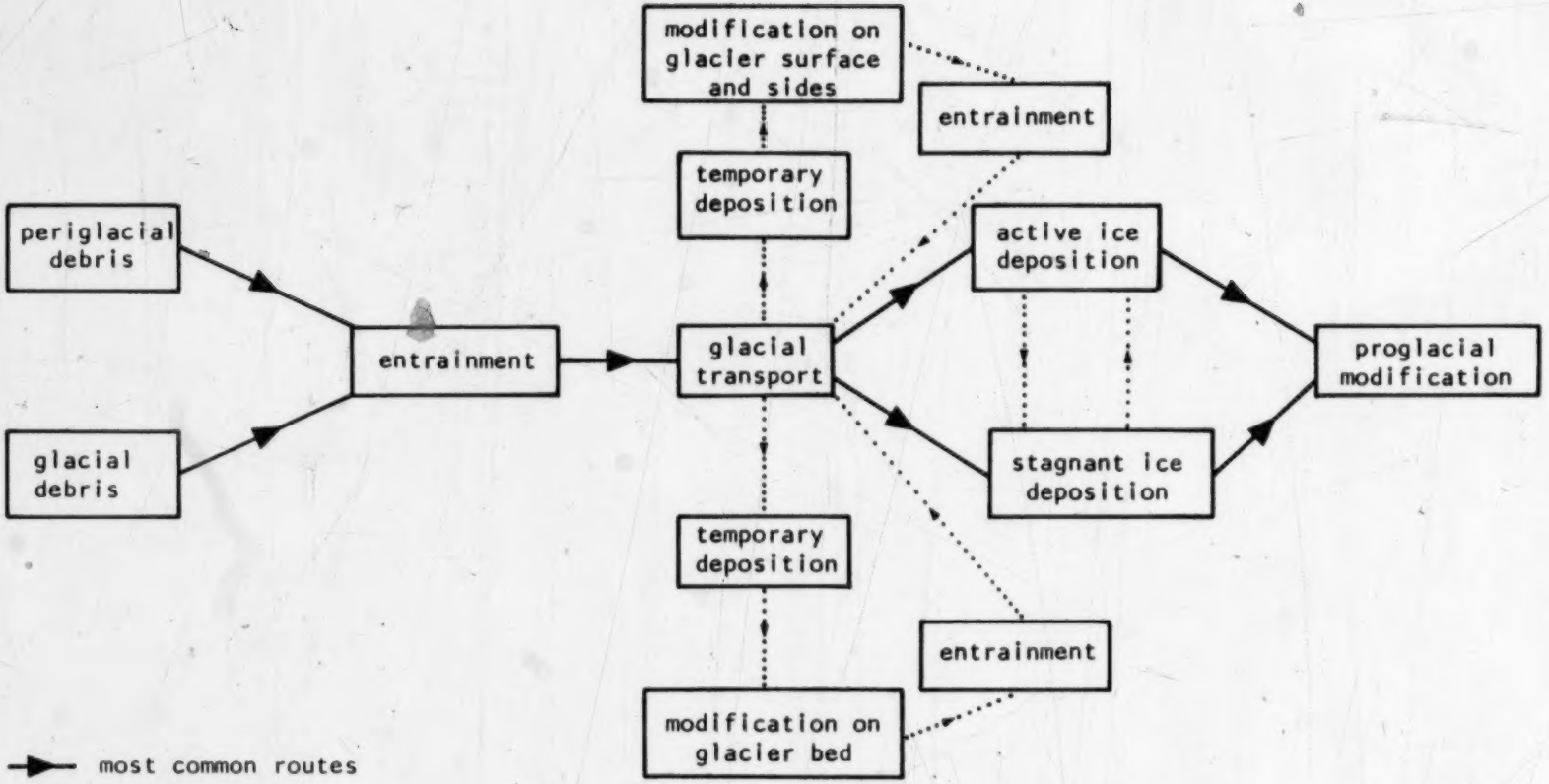
The formation of till has received much attention in the past two decades. Both terms *till formation* and *till deposition* are used interchangeably in the literature. Debris release from ice and subsequent collapse or redistribution is a dynamic process, particularly in the superglacial environment where buried ice is of major importance (Kemmis *et al.*, 1981). Therefore *till formation* "is completed when the particles of glacially derived debris that make up the till framework are mainly in contact" (Shaw, 1982, p. 1548). Only when till is in its resting place following deglaciation can it be called *deposited* (Shaw, 1982).

Till, as we observe it in various landforms, has undergone many processes prior to deposition. Broad, process-related categories or stages may be recognized; initiated by glacial erosion and entrainment, through transport, to formation and deposition. Sugden and John (1976) have presented a flow diagram (Figure 2.1) which represents the stages through which the related particles might pass.

Glacial Erosion and Entrainment:

Glacial erosion and entrainment are considered together here insofar as some processes of erosion (e.g. abrasion) require that material already be entrained. Also, effective erosion is unlikely to occur unless the debris that is produced is moved up into the glacier (Sugden and John, 1976). Finally, entrainment in some cases can not be separated easily from the erosion process (e.g. large-scale block inclusion).

Glacial erosion is usually discussed in terms of abrasion and quarrying (plucking) processes (Sugden, 1978). The product of these forms of erosion range in size from clay to boulders (Dreimanis, 1976) and are subglacially entrained, depending upon the thermal and hydrological characteristics, via two major mechanisms; regelation and tractive force incorporation (Weertman, 1961; Kamb and La Chapelle, 1964; Boulton, 1970a,



(Sugden and John, 1976)

Figure 2.1 The stages through which detrital particles might pass in a glacier system

1972, 1975).

Subglacial debris entrainment is obviously difficult to observe and thus related hypotheses remain unproven. However, debris within regelation layers of basal ice has been frequently observed (Kamb and La Chapelle, 1964; Boulton, 1970b). It is thought that small particles are frozen onto the base of the glacier in the lee zones of obstacles where lower pressure occurs. The amount of debris entrained by this method is limited as the regelation layers tend to be destroyed by pressure melting as the sliding ice meets another bed protuberance (Sugden and John, 1976).

Tractive force incorporation requires that the moving ice overcomes the frictional resistance exerted between the bed and particle. The active ice may deform around an isolated block and increase the contact between ice and rock, thereby increasing the tractive force. However, critical conditions of ice thickness exist. The ice must be thick enough to deform around the block yet not be too thick that the tractive forces cannot overcome the resistance with the bed (Sugden and John, 1976).

Moran (1971), Shaw (1971), Clayton and Moran (1974), Christiansen and Whitaker (1976), Eyles and Slatt (1977) and Moran *et al.*, (1980) have described mechanisms whereby large, intact, blocks of bedrock or pre-existing glacial drift are incorporated into the ice. Moran's (1971) proposal was based upon the relationship between effective normal stress and the shear strength of the material being entrained. He used effective normal stress, defined by Terzaghi and Peck (1967), as normal stress minus the porewater pressure. Thus, increased porewater pressure decreases the effective normal stress and ultimately the shear strength of the material. Moran (1971) suggested that three conditions must be met to permit shear failures in material overridden by glacier ice and allow incorporation. First, the overridden material must contain permeable beds confined by less permeable beds. Secondly, groundwater flow must be modified such that water moves into these confined beds, generating elevated porewater pressure. He suggested that material need not be frozen at the time of incorporation if porewater pressure in subjacent beds is sufficiently high. Thirdly, a compressive flow regime is essential whereby flow in the ice is upward from the base (Figure 2.2). Clayton and Moran (1974), Christiansen and Whitaker (1976), Eyles and Slatt (1977) and Moran *et al.*, (1980)

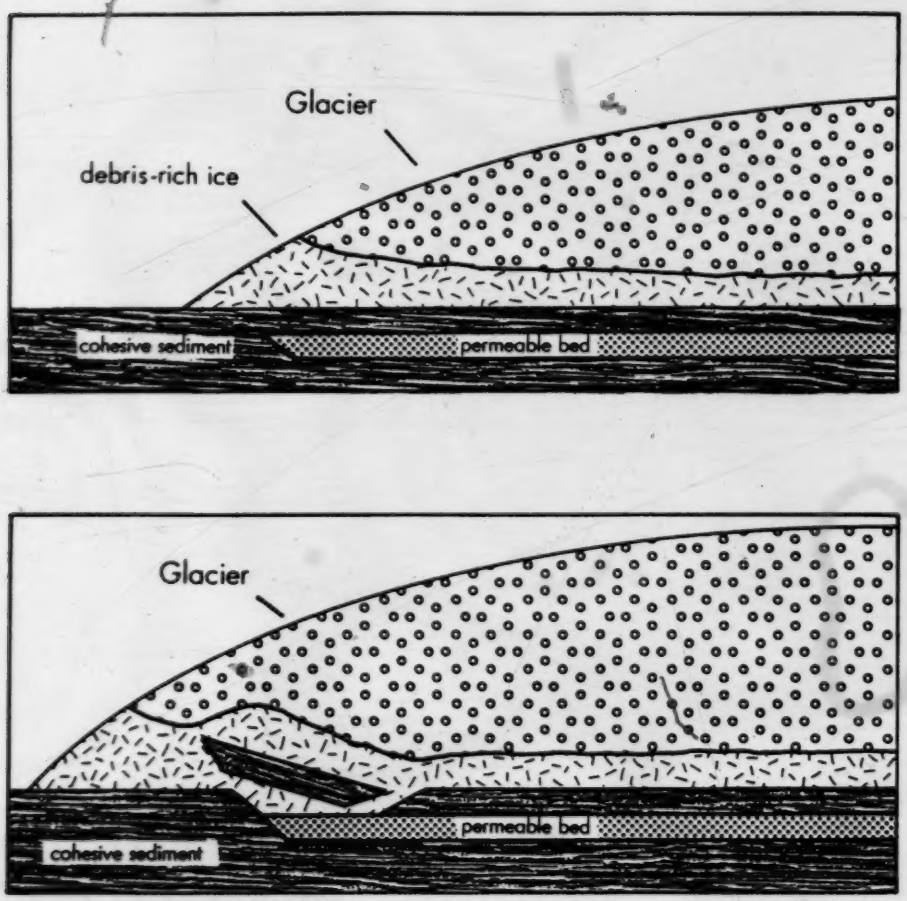


Figure 2.2 A schematic drawing of large-scale block inclusion resulting from elevated porewater pressures (after Moran, 1971)

suggested further that the advancing glacier must be frozen to the substrate and the movement is primarily by internal deformation of ice. Thus, specific geohydraulic, glacier flow, and thermal conditions must be met for thrust blocks to be plucked from the bed.

Shaw (1971) dealt primarily with thermal and hydrological conditions at the base of glaciers. Extending the work of Weertman (1961) he illustrated, for example, how stratified lacustrine sediments, initially unfrozen, may have been incorporated into the base of a glacier. Shaw (1971) envisioned zones of basal melting, well upglacier from its margin, due to increased ice thickness and basal sliding. Meltwater so produced flowed down the pressure gradient towards the glacier margin. Between the glacier margin and basal melt zones, meltwater refreezing took place. As the glacier advanced the increased ice thickness brought part of the laminated sediments into the zone of basal freezing. Clean ice formed below these laminated sediments and sediments were lifted into the glacier and transported away.

Debris in Transport:

Once entrained debris may be transported in basal, englacial or superglacial positions. The basal zone refers to the lower, relatively thin and debris-laden part of the glacier including the sole (Lawson, 1979). Its thickness is variable, ranging from 1 to 3 metres (Dreimanis, 1976) to 15 metres (Lawson, 1979). Here, the character of the ice and debris reflects the interaction with subglacial materials during flow and represents the main zone of comminution by crushing and abrasion (Lawson, 1979).

The englacial zone represents the main body of ice. Material is moved into this position from below by compressive flows at subglacial constrictions and at the frontal margins of the glacier (Nye, 1952). Alternatively, subglacial debris may be brought up into the ice along shear planes (Boulton, 1967). Alternatively, superglacial debris may be subducted into the englacial zone. In the englacial zone included clasts and/or thin debris bands are unaffected by surface or subglacial processes (Lawson, 1979). Under these conditions englacial debris may be transported for hundreds of kilometres if the glacier system is sufficiently large (Dreimanis, 1976). In the englacial zone rock fragments seldom collide and clasts may become aligned either parallel or transverse to the direction

of ice movement, depending upon local stress (Boulton, 1967).

Debris is moved into the superglacial position by strong upward movement in the zone of compressive flow. Subsequently, surface processes such as freeze–thaw, water action and wind action dominate and thus affect the characteristics of debris and ice. Sediments are also added to superglacial zones by mass movement, fluvial and aeolian processes.

2.2.3 Classification

The processes of till formation, which occur in different depositional environments, are the basis of classifications of till. Till has been differentiated on the basis of properties inherited from these processes (Kemmis *et al.*, 1981).

Till has been classified into two main types (subglacial, basal, or lodgement till and superglacial, englacial, or ablation till) since the start of investigations of tills about a century ago (Dreimanis, 1976). Thus subglacial, active, mechanical processes were differentiated from superglacial/englacial, passive, melt–out processes. This twofold genetic classification dominated until Boulton (1971) improved upon it and subdivided ablation till into melt–out till and flow till, based upon their stratigraphic characteristics and ease of differentiation. Later, both Boulton (1976) and Dreimanis (1976) proposed more detailed classifications based upon formational processes and distinguishing characteristics (Tables 2.1 and 2.2). Shaw (1977a, 1982) expanded these classifications into a non–hierarchical scheme (Table 2.3) whereby different column combinations could be extracted to provide a high level of interpretation.

Lodgement Till:

Subglacially formed, lodgement till develops as particles in debris–rich ice are *plastered* onto the subglacial surface. Boulton (1975) stated that lodgement is a mechanical process which will occur when frictional forces between a particle in traction and the bed exceed the tractive forces exerted by the moving ice. Secondly, pressure melting of sliding basal ice against obstructions in the bed will release small particles as regelation melt–out (Boulton, 1971). Boulton (1975) and Sugden (1978) maintained that

Sedimentary association	Source of material	Principal till types	Sub-type
Part of the supraglacial sediment association	Supraglacially derived	Supraglacial morainic till	
Part of the subglacial sediment association	Subglacially derived	Flow till	Allochthonous
			Parauthonous
		Melt-out till	Autochthonous
		Lodgement till	Deformed
			Undeformed
		Lee-side till	

Table 2.1 A classification of tills (Boulton, 1976)

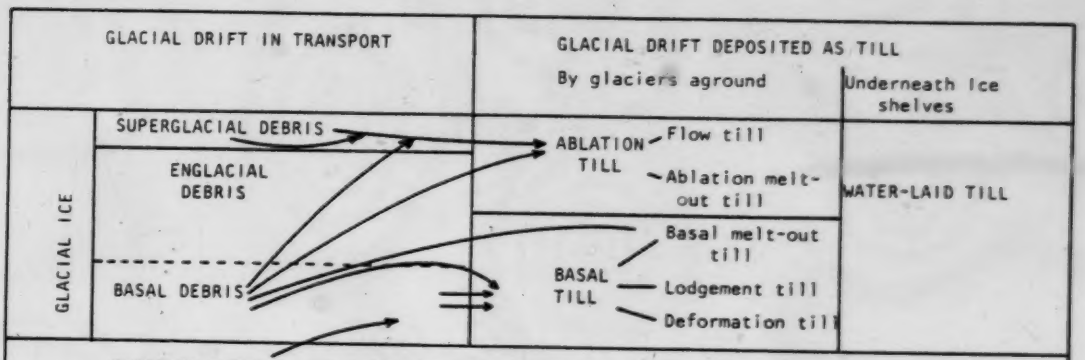


Table 2.2 A genetic classification of tills and their relationship to glacial debris in transport (Dreimanis, 1976)

Position of transport	Position of deposition	Process of deposition	Tectonic facies
Supraglacial	Proglacial	Lowered	Highly attenuated
Englacial	Lateral ice-contact	Flow	Poorly attenuated
Basal	Supraglacial	Melt-out	
	Subglacial	Sublimation	
		Lodgement	

Table 2.3 Classification of terrestrial tills (Shaw, 1977a)

the flowing basal ice must be at or near pressure melting point for these lodgement processes to occur. As well, thrusting and shearing, where active ice overrides stagnant ice, or previously deposited till (Boulton, 1970b, 1971; Lawson, 1979; Kemmis *et al.*, 1981), may be considered essential for the lodgement processes (Moran, 1971).

Lodgement till will largely inherit the pebble fabric from the internal dynamics of glacier movement (Lavrushin, 1970; Boulton, 1971, 1976; Marcusson, 1975; Sugden and John, 1976; Lawson, 1979). The fabric may be slightly reoriented as interstitial ice melts out (Kemmis *et al.*, 1981) or reoriented to a larger extent as a result of deformation by overriding ice (Ramsden, 1970; Ramsden and Westgate, 1971; Mark, 1974) or in response to variations in the subglacial bed configuration (Boulton, 1971; Lawson, 1979).

Melt-Out Till:

Melt-out till is perhaps the most common type of till, straddling both the subglacial environment (basal melt-out till) and the superglacial environment (ablation melt-out till) (Boulton, 1972; Dreimanis, 1976). Melt-out till is formed by the passive *in situ* melting of stagnant, non-deforming, partially debris-laden ice under confining conditions (Harrison, 1957; Boulton, 1970, 1972; Lawson, 1979; Kemmis *et al.*, 1981). Two melting zones are recognized in buried stagnant ice (Figure 2.3). The eventual removal of ice is primarily a function of heat sources and insulation effects.

Basal Melt-Out Till:

Melting of the lower stagnant ice zone is determined mainly by the geothermal heat flux and temperature gradient in the ice (Boulton, 1970b). Nobles and Weertman (1971) have shown that bed surface irregularities will affect both the geothermal heat flow and the thermal gradient. There will be increased heat input by heatflow refraction and decreased thermal gradient at depressions. Thus the rate of debris release will be highest over depressions and lowest over high points, tending to smooth out the bed configuration.

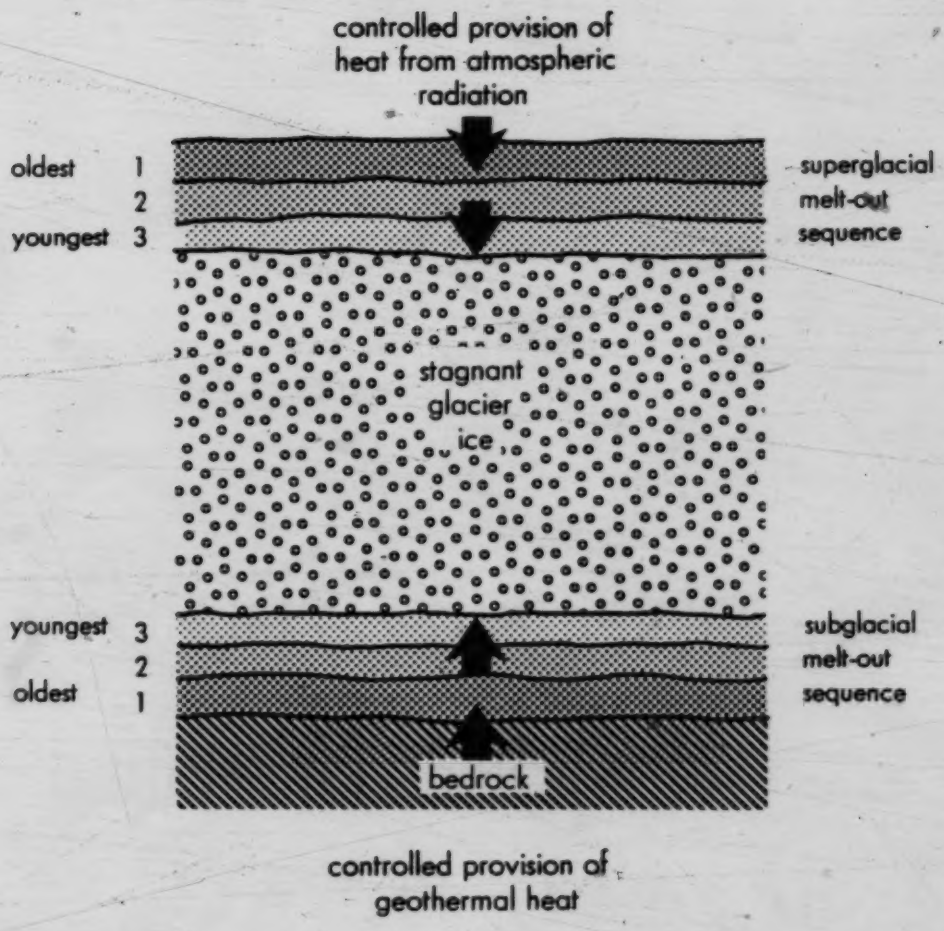


Figure 2.3 The two melting zones in buried stagnant ice

(Sugden and John, 1976)

If meltwater generated by upward melting of the basal ice layers is not evacuated this may lead to till saturation and excess porewater pressures (Boulton, 1971). Lateral flowage or internal deformation may occur under these undrained conditions (Boulton, 1971; Sugden and John, 1976). These sedimentary units are analogous to Elson's (1961) *deformation tills*.

Ablation Melt-Out Till:

Ablation melt-out till is the result of debris release from exposed basal or englacial ice at the glacier terminus as well as from the upper surface of buried stagnant ice (Boulton, 1971; Kemmis *et al*., 1981). The major heat inputs are directly related to local climatic regimes plus heat from stream and pond water in contact with the ice.

The melting rate of the upper ice surface is controlled to a large extent by the thickness, distribution, morphology, textural characteristics and thermal conductivity of the superglacial debris cover. Various authors (Ostrem, 1959; McKenzie, 1969; Loomis, 1970; Loomis *et al*., 1970; Driscoll, 1974; Eyles, 1979; Lawson, 1979; Nakawo and Young, 1981) have presented both theoretical and field observations pertinent to the effects of this debris cover on buried ice melting. For example, Ostrem (1959) found that melting was greatly reduced where a heterogeneous debris cover thicker than 1 centimetre was present, whereas debris less than 1 centimetre thick accelerated melting. Boulton (1971) stated that only a 3 centimetre thickness in Svalbard, Spitsbergen, decreased the ablation rate of the underlying ice. McKenzie (1969) noted that ablation continued even with a 4 metre thickness of coarse-grained debris in an ice-cored kame in southeast Alaska. Lawson (1979) stated that release of debris from basal ice of the Matanuska Glacier, Alaska proceeded even when the sediment cover exceeded 8 metres. Nakawo and Young (1981) showed that the water content of the debris cover will impose strong controls on the ablation rates as well as stored heat in a thick debris cover. Eyles (1979) suggested that an illuvial mud layer at the till/ice interface seals the ice surface retarding the rate of top melt. A stable phase is established when the mud layer is unbroken and ablation melt-out is minimal. This stable phase is usually followed by an unstable phase during which the debris cover/mud layer is disturbed and ice melting is

accelerated.

As passive *in situ* melting proceeds the debris which has been melted out may be deposited in various ways depending on local conditions (Kemmis *et al.*, 1981). First, it may be simply *let-down* under confining conditions. Such deposits show preservation of the englacial fabric, with only slight modification as sediment collapses due to readjustment of the grain contacts and particle packing (Boulton, 1971; Lawson, 1979). However, the texture and structure of debris are lost during melt-out (Lawson, 1979) as fine-grained sediment migrates downward into pore spaces between larger particles. This mixing is a function of the volume of sediment contained in the ice, and its distribution, as well as the texture of the debris (Boulton, 1970b, 1971).

A common variation is that the material is subjected to gravity flow and redistribution (Boulton, 1967, 1972, 1976; Marcusson, 1973, 1975; Lawson, 1979; Kemmis *et al.*, 1981). This has been generally referred to as *flow till* (Hartshorn, 1958; Boulton, 1968, 1971, 1972, 1976; Marcusson, 1973, 1975) but more recently as *sediment flow diamicton* (Lawson, 1979, 1981, 1982).

Sediment Flow Diamicton:

Acceptance of Lawson's (1979) genetic definition for till excludes the generally used term *flow till* for those sediments which are redistributed by gravity flow in the superglacial environment. The use of the term flow till had survived without much alteration in meaning since it was first introduced by Hartshorn (1958). Boulton (1968, 1971) firmly established the use of this term in the literature with his studies of the formative processes involved in the superglacial environment of modern glaciers in Spitsbergen. Lawson (1979) was the first to challenge its use although hints of discontent can be seen in Goldthwait (1971), Dreimanis (1976) and Sugden and John (1976). Even Boulton (1976) compromised to a certain extent in his later till definition in order to skirt the problem. Flow till is a prevalent term in the literature and will probably continue in use even with its inherent problems. However, for the purpose of this work the resedimented deposits in the superglacial environment are referred to as diamictons resulting from sediment flow (or, for brevity, diamicton).

Kemmis *et al.*, (1981, p. 21) provided a working definition of such resedimented glacigenic materials as;

> " deposits which have been subjected to flow, reworking and resedimentation on and/or next to the ice surface, and which derive their sedimentologic properties from the resedimentation processes; many of these deposits are till-like; ...".

Subaerial Sediment Flows:

Within the superglacial environment meltwater plays an important geomorphic role. If sediments are to be redistributed the amount of available meltwater will largely control the type and extent of debris flows as well as control the alteration of the sediment constituents (Boulton, 1968, 1971, 1972; Sugden and John, 1976; Lawson, 1979, 1981, Kemmis *et al.*, 1981). The nature of the slope and general surface roughness are also important variables in controlling the extent of flow and the number of resedimentation phases which may take place.

Boulton (1971) and Lawson (1979) have attempted to classify, using modern examples, subaerial flow types which are a reflection of the flow processes and the properties of the resulting sediments. Boulton's (1971) arbitrary classification of subaerial flow tills includes three basic flow processes: mobile liquid flow; semi-plastic flow; and downslope creep. The processes are differentiated by factors such as rate of movement, water content requirements, slope stability and morphology of the flowing mass, texture, structure and pebble fabric. Table 2.4 outlines characteristics of Boulton's (1971) flow till types.

Lawson's (1979) study of superglacial debris subjected to gravity flow and resedimentation in the snout zone of the Matanuska Glacier, Alaska, is comprehensive. He recognized four types of active, subaerial sediment flows (Table 2.5) which are distinguishable because of differences in their predominant deformation characteristics and mechanisms of grain support and transport. Properties of these flows suggest that they are transitional and represent a continuum related primarily to their water content. Saturation of the sediment will reduce the shear strength and even at low slope angles the material can fail. However, even on low-angle slopes, with minor water content, material

Flow Till Type	INTERNAL ORGANIZATION			Surface Forms	Basal Contact
	General	Structure	Fabric		
Mobile Liquid Flow	-subaerial flow -very high water content; above liquid limit - 10 cm depth of flow -upper, stone-free, rapidly moving element over a stony, slowly moving element	-well stratified	-body of flow; the a-axis parallel to flow direction -nose of flow; the a-axis transverse to flow direction	-elongate, with lobate form	-glacier ice
Semi-plastic Flow	-subaerial flow -shear strength exceeded due to surface loading or pore pressure -occurrence on more stable slopes -movement in a semi-plastic mass	-little stratification internally, but stratification at the surface of the flow	-body of the flow; a-axis parallel to flow direction -nose of the flow; a-axis transverse to flow direction -lateral margins; the a-axis parallel to flow direction	-lobate flow	-along arcuate slip-plane between unfrozen and frozen till, or unfrozen till and the glacier ice
Downslope Creep	-not exposed subaerially -lower autochthonous element (till derived from underlying ice) -slopes appear stable -low water content -stresses shear strength -speed of creep is a function of the rate of the underlying ice melt	-unstratified -compact	-prolate stones; the a-axis parallel to slope -blade-shaped stones; a-axis uncontrolled -much influence of the original englacial fabric	-little recognizable form	-glacier ice

Table 2.4 Characteristics of "Flow Till" Types (after Boulton, 1971)

Sediment flow type	Bulk texture	Internal organization			Surface forms	Contacts and basal surface features	Pene-contemporaneous deformation	Geometry and observed maximum dimensions (lengthxwidth, thickness, m)
		General	Structure	Pebble fabric				
1	Gravel-sand-silt, sandy silt	Clasts dispersed in fine-grained matrix	Massive	Absent to very weak; vertical clasts. S_1=0.49-0.55	Generally planar; also arcuate ridges, secondary rills and desiccation cracks	Non-erosional, sharp, load structures	Possible subflow and marginal deformation during and after deposition	Lobe; 50 x 20, 2.5
2	Gravel-sand-silt, sandy silt, silty sand	Plug zone; clasts dispersed in fine-grained matrix	Massive; intraformational blocks	Absent to very weak; vertical clasts	Arcuate ridges; flow lineations, marginal folds, mud volcanoes, braided and distributory rills on surface	Non-erosional, contacts indistinct to sharp load structures	Possible subflow and marginal deformation during and after deposition	Lobe; 30 x 20, 1.5 Sheet of coalesced deposits
		Shear zone; gravel zone at base, upper part shows decreased silt-clay and gravel	Massive; may appear layered	Absent to weak; bimodal or multimodal S_1=0.50-0.65				
3	Gravelly sand to sandy silt	Matrix to clast dominated; lack of fine-grained matrix possible; basal gravels	Massive; intraformational blocks occasional	Moderate, multimodal to bimodal parallel and transverse to flow S_1=0.60-0.70	Irregular to planar; singular rill development mud volcanoes	Non-erosional contacts indistinct to sharp	Generally absent; possible subflow deformation on liquified sediments	Thin Lobe; 20 x 10,0.5 Fan wedge 30 x 65, 3.5
4	Sand, silty sand	Matrix except at base	Massive to graded	Absent	Smooth, planar mud volcanoes	Conformable	Absent	Thin sheet; 20 x 30, 0.3

Table 2.5 Characteristics of sediment flow deposits, terminus region, Matanuska Glacier, Alaska (Lawson, 1979)

can fail by shearing along the sediment (or sediment/ice) interface at the base of the flow when some critical thickness is reached. This happens when the gravitationally applied stress exceeds yield strength. In this type of failure the body of the flow maintains its strength because movement is along a discrete zone at the base of the displaced material.

It is therefore the interactions of sediment texture and thickness, slope, and available water supply which separate the different flow types. Flows will range from those which are fully liquified, allowing partial sorting of material as larger particles sink, through unsheared *plug* flows and rotational block failures, to low-angle basal sliding on underlying ice. The last type may occur in response to excess porewater pressure at the ice/sediment interface.

Detailed analyses of pebble fabrics from subaerial sediment flows on modern glaciers (Boulton, 1971, Lawson, 1979) show a high degree of variability. Mark (1974) suggested that these fabrics must be considered in relation to the direction of the flow which can be unrelated to the direction of ice movement. Lawson (1979) agreed that the fabrics are directly related to the resedimentation processes and that each type of flow should therefore yield different fabrics. As water content increases, the scatter of orientations decreases and preferential orientation develops with alignment parallel to sediment flow direction. Weaker orientation will exist in materials which have flowed with low water content.

Boulton (1971) found that for prolate and blade-shaped pebbles fabrics can vary considerably within the same flow unit. Also, in mobile liquid flow the *a* axes of pebbles tend to align themselves parallel to the direction of transport in the body of the flow and transverse in the nose. As well, in semi-plastic flow, variations of preferred dip orientation for different parts of the sediment flow are prominent (Figure 2.4) and with increased water content there is an increased dip of pebble long axes.

From this discussion it can be seen that fabrics of subaerial sediment flow deposits are variable. Thus, conclusive answers cannot be reached using fabric analyses alone.

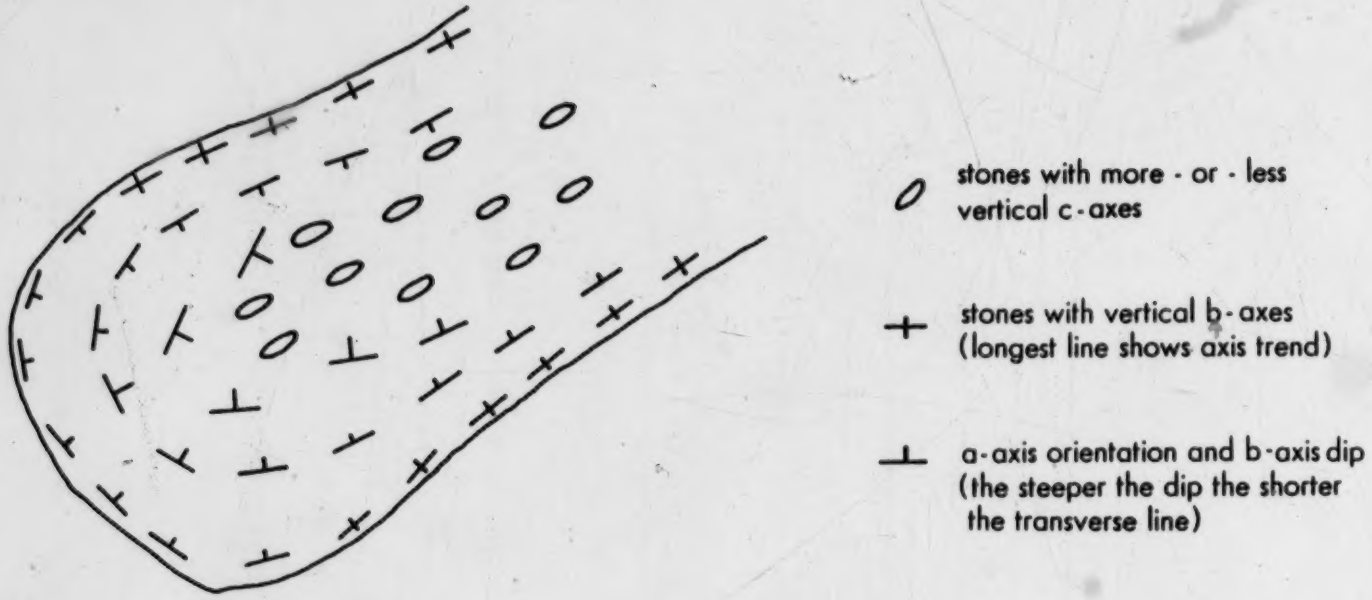

stones with more - or - less vertical c-axes
stones with vertical b-axes (longest line shows axis trend)
a-axis orientation and b-axis dip (the steeper the dip the shorter the transverse line)

Figure 2.4 Idealized lobate till flow showing the pattern of orientations which would be taken up by blade-shaped particles (after Boulton, 1971)

Subaqueous Sediment Flows:

Both Boulton (1971) and Lawson (1979) discussed subaerial sediment flows. However, May (1977) and Evenson *et al.*, (1977) have considered subaquatic environments. Evenson *et al.*, (1977) interpreted the interbedded relationship between laminated tills and current-deposited clastic units as *subaquatic flow till* or *subaqueous debris flows*. May (1977) proposed a term *lacustrotill* for these till-like sediments deposited by flow mechanisms.

Various criteria such as clast fabrics, sole marks, flow folds, lack of graded bedding, granulometric composition and depositional geometry have been employed to show that till units were the product of material slumping from the glacier ice into a body of water (Evenson *et al.*, 1977). Clast fabric maxima in subaqueous sediment flows, like those of subaerial flows, are usually parallel to the downslope flow. However, others may be transverse or oblique to the flow.

2.2.4 Diagnostic Criteria Examined in the Field

The diagnostic criteria of diamicton/till identification are not universally standardized (Dreimanis, 1971; Johansson, 1975; Raukas, 1975). *Diamicton* was a term first applied to all "essentially non-sorted, calcareous, terrigenous deposits composed of sand and/or larger particles in a muddy matrix" (Flint *et al.*, 1960, p. 507). Only after considering all pertinent information should one conclude that the diamicton is indeed till deposited directly by glacial ice. Boulton (1976a) and Lawson (1979) have provided outlines of comprehensive, diagnostic, criteria for till type discrimination (Tables 2.6 and 2.7 respectively). The objectives of the present research necessitated selection of descriptive and quantitative properties to be studied. In this section only those diagnostic criteria judged significant for genetic interpretation will be discussed.

Texture:

Texture, the grain size properties of both the matrix particles and contained clasts, has been routinely considered in investigations of diamicton/till genesis. Marked variability of texture, particularly the matrix grain size proportions, has often aided in unit

PROPERTIES	FLOW TILL	MELT-OUT TILL	LODGEMENT TILL
Nature of sequence and position of tills within it	Topmost of a sequence of tills. Often occurs directly above ice-contact outwash sediments. May coat hummocky terrain as a thin veneer. Sediment lenses of all sizes occur within the flow till	Occurs directly above lodgement till or eroded surface. Always overlain by sediment overburden	Occurs at the base of a sequence of sediments derived from glacier retreat
Grain size composition and its spatial variation	Often shows considerable variations in grain size composition. Local enrichment and depletion in fines due to subaerial washing on till surface	Relatively small spatial variation in grain size composition	Relatively small spatial variation in grain size composition. May show boulder clusters of glacitectonic inclusions from underlying beds
Banding	Shows both sedimentary banding and shear banding. The former due to water sorting on the till surface, the latter due to streaking out during flow	Absence of banding	Absence of sedimentary banding but shear banding due to inclusion and streaking out of sub-till sediments
Clast orientation fabrics. Largest commonly occurring clast should be selected as the most reliable	Transverse and parallel to flow direction. Often parallel and transverse to ice flow direction, but not necessarily. Large within-site fabric variability	Little studied, but well-defined transverse and parallel orientations probably develop. The a-b planes tend to lie in plane of bed. High within-site fabric consistency	Tendency for the development of strong parallel fabric peaks with up-glacier dip, except for those tills where post-depositional deformation has occurred, such as in flutes or folds transverse to flow. Strong within-site and between-site correlation
Folding and faulting	Intra-formational folding due to flow, commonly seen asymmetric overturned or flat-lying isoclinal fold noses preserved. Frequently overlie stratified sediments which show gentle folding and high angle faulting indicative of collapse over melting stagnant ice	No internal folding	Folding may be apparent when underlying beds have been incorporated. Folds generally isoclinal with flat-lying axial planes. Anticlinal fold noses rarely preserved. Synclines facing up-glacier commonly found. Fold noses often completely streaked out. Folding in underlying beds similar to that in the till, though it may be less extreme. Structure reflect subglacial shearing
Jointing	Joints primarily reflect drying out (vertical, polygonal in plan), and freezing (closely spaced and parallel to the surface	Rarely jointed	Joints primarily reflect unloading (parallel to surface, more widely spaced than joints due to freezing), and shearing (sub-parallel lenticular joints sets, or vertical conjugate sets)
Surface expression	May occur below a low relief, slightly irregular surface, or below an irregular hummocky ridged surface, or a series of ridges lying parallel to the glacier margin	Never exposed at surface	Almost invariably fluted and/or drumlinised in the direction of ice movement. May have transverse pushed ridges superimposed, or an irregular pattern of till squeezed up into crevasses
Till thickness	Extremely variable, from very thin to very thick. Average thickness unlikely to exceed 1-2 metres	Thin, unlikely to exceed 2 metres	Any thickness. Average thickness may be large

Table 2.6 Criteria for distinguishing tills of different origin (Boulton, 1976)

Table 2.7 Some characteristics of the deposits, terminus region, Matanuska Glacier, Alaska (after Lawson, 1979)

Process	Deposit	INTERNAL ORGANIZATION			Contacts-basal surface features	Geometry-minimum dimensions
		General	Structure	Pebble fabric		
Lodgement at glacier sole	Lodgement till	Clasts randomly dispersed to clustered in matrix	Massive; shear foliation, other "tectonic" features dense, compact	Strong; unimodal pattern; orientation influenced by ice flow and substrate; low angle of dip	Image of substrate	Discontinuous pockets or sheets of variable thickness and extent
Buried ice melt	Melt-out till	Clasts randomly dispersed in matrix	Massive; may preserve individual or sets of ice strata	Strong; unimodal parallel to local ice flow; low angle of dip	Upper sharp, may be transitional; subice probably sharp	Sheet to discontinuous sheet; km^2 to m^2 in area, m thick
Sediment Flow	Sediment flow Type 1	Clasts dispersed in fine-grained matrix	Massive dense	Absent to very weak; vertical clasts	Non-erosional conformable contacts; contacts indistinct to sharp; load structures	Lobe; maximum of 1000 m^2 in area, 2.5 m thick
	Sediment flow Type 2	Plug zone; clasts dispersed in fine-grained matrix	Massive; intraformational blocks	Absent to very weak; vertical clasts	Non-erosional conformable contacts; contacts indistinct to sharp	Lobe; maximum 600 m^2 in area 1.5 m thick; sheet of coalesced deposits
		Shear zone; gravel zone at base, upper part may show decreased silty-clay and gravel content	Massive; deposits may appear layered where shear and plug zones distinct in texture	Absent to weak; bimodal or multimodal; vertical clasts		
	Sediment flow Type 3	matrix to clast dominated	Massive; occasional intraformational blocks	Moderate;	Non-erosional conformable contacts; contacts indistinct to sharp	Thin lobe; 200 m^2 in area; 0.5 m thick; fan wedge fills surface lows of irregular size
	Sediment flow Type 4	Matrix, except at base, where granules possible	Massive to graded	Absent	Contacts conformable; indistinct	Thin sheet; 200 m^2 in area; 0.3 m thick fills surface lows of irregular size and shape

differentiation. The concept of particle size defies simple definition (Pettijohn, 1975; McAllister, 1981). A comparison of clast diameters with those of equivalent spheres is implied in most definitions but these are not often directly measured (Pettijohn, 1975). In this study the Wentworth–Lane grade scale was used to define the upper boundary of each particle size fraction. The heterogeneous mixture of grains within the diamicton matrix was tactually classified following a ternary system based upon the proportions of the three components; sand, silt and clay.

Particle form is defined as "the resultant of combining those elements which affect the three–dimensional geometrical configuration of the surface envelope that contains the particle mass" (Orford, 1981, p. 86). Components of clast form include shape, roundness and surface texture. Only clast roundness, involving an evaluation of the sharpness of edges and corners of particles (Pettijohn, 1975), was assessed in the field. Figure 2.5 illustrates the chart employed for clast roundness estimations.

Degree of Consolidation:

Consolidation is the reduction in volume a mass undergoes when subjected to a compressive stress (Kemmis *et al.*, 1981). A sample can be considered overconsolidated if the preconsolidation pressure is greater than the stress exerted by the present overburden. Sediments will compact when subjected to an overburden pressure if allowed to freely drain. Even after the stress is removed the sediment will rebound only slightly and retain the effects of preconsolidation (Kemmis *et al.*, 1981).

Although the geotechnical properties of the diamicton/till were not directly measured in the field, the degree of consolidation or compaction was assigned a qualitative rank: friable, compact or very compact. In general, basal till tended to be more dense and overconsolidated and thus this criterion occasionally allowed differentiation of till units. However, recent investigations (Boulton and Paul, 1976; Dreimanis, 1976) have shown that this generalization may be too simplistic because tills may be deformed during or after deposition to develop a looser structure. Alternatively, if subglacial water drainage was inhibited, compaction would be reduced. Finally, desiccation of flow tills (Boulton, 1976) may produce high preconsolidation values and thus preclude this criterion

of differentiation between basal till units and flow till units.

Structure:

Structure is amongst the most diagnostic criteria for the interpretation of diamicton/till. In the study area such structural attributes varied greatly, both within and between sites, and it was therefore difficult to follow a standardized format in their description. However, it was necessary to consider a wide range of possibilities and these are briefly discussed as follows.

Till structure tends to be massive, without lamination or graded bedding (Goldthwait, 1971). Yet bedded and laminated tills, as well as tills with stratified intrabeds and block inclusions, do occur. The sand and silt lenses maintained attitudes which were horizontal, inclined and vertical. Sometimes these lenses pinched out or interfingered with others. The contacts were planar or undulatory, concave or convex. Block inclusions were unconformable and displayed similar relationships with the diamicton/till as did the lenses.

Jointing is an important component of structure and is usually attributed to compaction or post-depositional desiccation. An appraisal of the basic joint types and their spacing, at times, allowed a preliminary separation of the diamicton/till units. Major joint types include columnar, blocky, prismatic and platy (Figure 2.6).

Deformation structures evolve in response to internal and external stresses. These structures may be syngenetic or epigenetic. Elastic fracturing yields faults and shear structures while quasi-plastic deformation creates folds. Various types of faults and folds may exist within a single exposure. Fault penetration of, or truncation between, units was valuable for the interpretation of the till. Fold axes reflected predominant directions of applied forces. Diapiric or injection structures were also recognized at some locations. These are a response of underconsolidated sediments to differential loading.

Roundness Classes: A: angular; B: subangular; C: subrounded; D: rounded; E: well rounded

Figure 2.5 Clast roundness classes (Pettijohn, 1975)

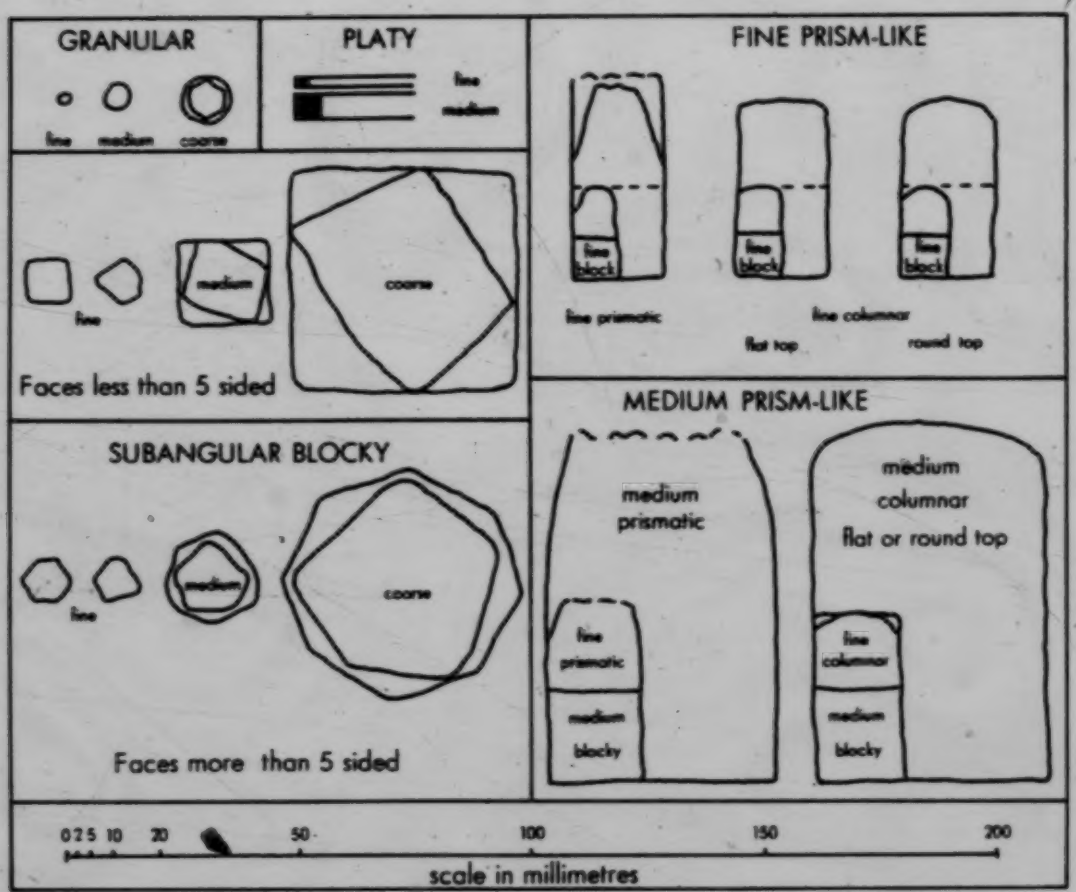


Figure 2.6 Joint Types

Pebble Orientation (Till Fabric):

The tendency for coarse clasts to have preferred orientations occurs because an ovoid will become oriented in a direction which corresponds to an equilibrium condition of an applied force (McGreal, 1981). Fabric analysis is the study of this orientation as well as its geomorphic implications (see Appendix 1). The azimuth, measured from true north in a down-dip direction, and the plunge below the horizontal of the long axis (*a*) of pebbles, are graphically and statistically combined to demonstrate the pebbles' orientation in space (Andrews, 1971a; McGreal, 1981) (see Appendix 1).

Fabrics were measured at a number of exposures. Fifty pebbles represented a sample at each fabric site. The exposure was first cleared of all loose surficial debris with a trowel. The vertical face was then slowly excavated within an area of 0.5 m^2 until a suitable pebble was located. Pebbles which lay adjacent to large boulders were not measured. Each pebble was carefully removed and examined to ascertain whether it had the necessary minimum 3:2/*a:b* axes ratio (Evenson, 1971). In most cases the silty clay matrix allowed a cast to remain once the pebble had been removed. If suitable, the pebble was then reinserted and the long-axis was measured using a Brunton pocket transit. Directions were measured as precisely as possible but, realistically, an error of $\pm 2^{\circ}$ is expected. Dip measurements are subject to even greater error. To help minimize this error a wooden stick was inserted into the cast to duplicate the plunge of the *a* axis. Dip measurements were made directly on the stick with a Brunton pocket transit. Finally, the pebble was discarded to prevent accidental re-measurement.

2.3 Glaciofluvial and Glaciolacustrine Sediment Properties

2.3.1 Definitions

Glaciofluvial deposits are defined by Lundquist (1979, p. 5) as sediments which have been "transported and deposited by streaming water generated by melting of glacier or inland ice". As a natural continuum, these meltwater streams often debouch into standing water. Finer material is carried out into a lake basin and accumulates as glaciolacustrine sediments. Deltaic sedimentation often links the two environments.

The position of deposition, relative to the ice mass, has been traditionally used to distinguish two major sedimentary environments; ice-contact and proglacial (Flint, 1971; Shaw, 1972; Price, 1973; Lundquist, 1979). Within the ice-contact environment glaciofluvial deposition may occur subglacially, englacially, superglacially and/or against the glacier margin. Glacier lakes may form either superglacially or proglacially. Thus a variety of distinctive sedimentary environments exist and consequently the deposits are varied.

These relations are perhaps best exemplified on a decaying, stagnant ice mass. Sedimentation may occur along any number of spatially and temporally changing margins. Difficulties are rife when one attempts to distinguish *true* glaciofluvial or glaciolacustrine deposits. The very nature of ice disintegration allows some areas to become temporarily depressed with respect to the surrounding ice surface. These depressional areas may become short-lived collection zones for superglacial or ice-walled lakes, base-levels for inflowing meltwater and localized sediment *sinks*. Further problems are posed by deposits formed at contact zones between glaciofluvial and glaciolacustrine environments. Here, overlapping of sedimentary units is expected to occur.

2.3.2 General Depositional Processes

The processes of primary deposition in glaciofluvial environments are, in part, similar to those in *normal* fluvial systems. However, ice imposes controls on flow regime, stream velocity (Sugden and John, 1976) and channel characteristics (Shaw, 1972) which are uncommon in *normal* fluvial environments. In addition, variations of sediment input are often relatively large and rapid in the varied environments of glaciated zones. Flow regime is strongly influenced by the rate of ice melting. As a consequence large fluctuations of discharge within a glaciofluvial setting are common, both in the long and short term (Price, 1973; Sugden and John, 1976). Streamflow variations are strongly seasonal. Discharge differences may also be expected to have marked diurnal characteristics.

Meltwater stream velocities not only vary in direct response to irregular meltwater production but may be locally influenced by such other controls as ice dam collapse or blockage by mass movement. Ice slope variations are likely to be rapid in a disintegrating ice mass, particularly near the margin of the glacier system. Channel configuration and

evolution therefore may be controlled to a large extent by the confining ice walls. Englacial meltwater channels are restricted laterally as little or no migration is allowed (Shaw, 1972). Such stream beds are lowered and raised by erosion and deposition (Shaw, 1975; Sugden and John, 1976).

Processes of sedimentation in various types of glacial lakes have been discussed at length by numerous authors (e.g. Price, 1973; Ashley, 1975; Gustavson, 1975; Gustavson *et al.*, 1975; Shaw, 1975; Theakstone, 1976; May, 1977; Orombelli and Gnaccolini, 1978). It is generally agreed that density currents play an important role in glaciolacustrine sedimentation. Ashley (1975) suggested that density underflows are the major mechanism of sediment distribution in these lakes. Density underflows result from high suspended load concentrations of meltwater streams pouring into lake water bodies which have lower concentrations. To a great extent these flows are controlled by the diurnal and seasonal fluctuations of meltwater and debris supply. Other factors which influence the sedimentary character of glaciolacustrine deposits are, for example, depth of the lake, the water temperature and the probability of ice rafting (Price, 1973).

2.3.3 General Characteristics of Glaciofluvial and Glaciolacustrine Sediments

Glaciofluvial deposits are typically stratified with rounded and sub-rounded particles. However, in some cases they may be massive or structureless. Sediments deposited almost entirely from suspension can yield a structureless unit (Banerjee and McDonald, 1975). Glaciofluvial sediments are generally well sorted, although this sorting may be restricted to discrete beds.

The stratigraphy of glaciofluvial deposits is frequently variable; for example, beds are often truncated. If stream velocity increases or meltwater streams are allowed to migrate laterally whole beds can be removed by erosion. Also, in contrast to most alluvial sequences, coarsening-upwards is often apparent (Shaw, 1972). Glaciofluvial sediments can also be capped by till. This is often the case where the outwash material formed in a ice-contact position or intraglacially (Eyles and Slatt, 1977; Orombelli and Gnaccolini, 1978; Clemmenson and Houmark-Nielson, 1981; Fraser and Cobb, 1982).

Glaciolacustrine sediments often include laminations. These may be rhythmites or varves, which are apparent because of changes in grain size. Rhythmites are comprised of couplets of one coarse and one fine layer, with no time or seasonal connotation attached to their recognition. Varves are couplets dominated by winter and summer beds deposited in one year (Price, 1973; Ashley, 1975). Turbidity currents, resulting from density underflows along the bottom of a lake, are often responsible for the laminated sands and silts that characterize the summer layers of varved sediments (Gustavson, 1975).

In addition to the characteristic laminated bedding individual clasts or blocks of previously frozen clastic sediments may be found within glaciolacustrine deposits. Ice-floe rafting is assumed to be the major mechanism by which these apparently disproportionate clasts or blocks are transported. Calving, lake-ice and river-ice are the sources of these ice floes.

2.3.4 Diagnostic Criteria Examined in the Field

The following criteria were evaluated for this study. Glaciofluvial and glaciolacustrine sediments are discussed together because much overlap exists in their description.

Texture and Shape:

A grain size comparator (Figure 2.7) was used to describe the approximate grain sizes characteristic of sedimentary units. The roundness of sand grains was assessed using Pettijohn's (1975) chart (Figure 2.5).

Sorting:

Sorting is a measure of the relative homogeneity of particle sizes within a sample and usually represents the completeness to which the sediments had been reworked by transporting agents (Compton, 1962). Most glaciofluvial and glaciolacustrine sediments were well sorted. However, good sorting was usually restricted to a single strata whereas bulk samples from a series of beds showed less sorting. Bimodal sorting, whereby the

interstices among large particles are filled with fine-grained particles, was also quite common. These sediments are still considered well sorted (Lundquist, 1979). The degree of sorting of sediments was approximated in the field by use of a comparative chart (Figure 2.8).

Structure:

Structures within the glaciofluvial and glaciolacustrine sediments were classified into primary (syngenetic) and secondary (epigenetic) groups. Primary structures are the characteristic beds formed at the time of deposition. They are a direct result of the energy conditions of the depositing medium and the granulometric character of the sediment (Reineck and Singh, 1975). Penecontemporaneous structures were included as a sub-class of primary structures because they have developed intraformationally. This means that such structures evolved shortly after initial deposition. Penecontemporaneous deformation structures included gravitational slumping and sliding structures, convolute bedding, load-induced structures and frictional drag structures. Secondary structures included those which demonstrated post-depositional disruption or modification of the primary structures. The most prevalent secondary structures were faults and folds.

Palaeocurrent Analysis:

Palaeocurrent patterns, used in conjunction with primary and secondary structures and granular texture, are important in the interpretation of past sedimentary environments. Investigations of palaeocurrents have included measurement and analysis of pebble fabric (Rust, 1975) and primary sedimentary structures (McDonald and Banerjee, 1971; Aario, 1972; Shaw, 1972, 1975; Saunderson, 1975). A wide range of sedimentary structures may be used in palaeocurrent analysis (Selby, 1976). However, cross bedding and ripple laminations are the most commonly used sedimentary structures (Potter and Pettijohn, 1963). Azimuth measurements of these structures usually demonstrate the former, flow directions (Potter and Pettijohn, 1963).

Palaeocurrents were taken from a number of sediment exposures. Details of location and stratigraphy, as well as the cross-bedded layer thickness, the individual bed

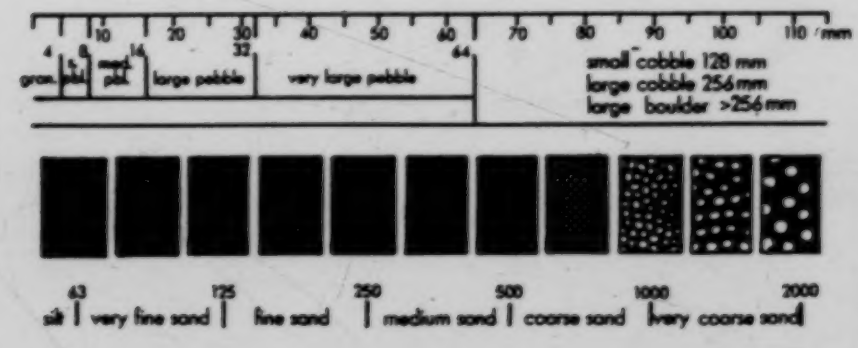


Figure 2.7 The grain size comparator used to describe the approximate grain sizes within sedimentary units

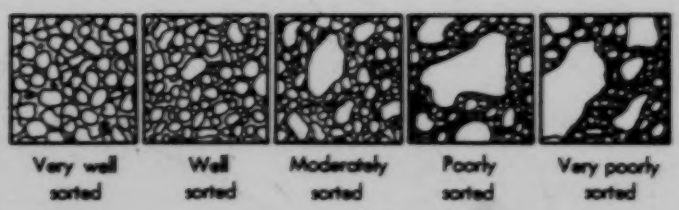


Figure 2.8 The comparative chart used to approximate the degree of sorting within sedimentary units

widths and the inclination of the beds, were recorded in order that this information might be integrated at the interpretation stage. The inclination of cross-beds is the angle between the foreset beds and the horizontal.

The identification of cross-bed types (tabular or trough), and measurement of their azimuth direction, required that a horizontal shelf be cut into the section. The excavation was done in a plane parallel to the boundary of the set at well defined cross-beds (Figure 2.9). Where the observed horizontal cross-stratification trace was straight (tabular cross-bedding) orientation was taken at right angles to this trace in the direction of the dip of the foreset beds (Figure 2.10). However, where the trace was curved (trough cross-bedding) palaeocurrent direction was measured normal to tangents at turning points of the traces (Shaw, 1975). Twenty-five measurements were made for each sample. The data were then plotted on two-dimensional rose diagrams. Because the preferred azimuthal pattern was unimodal the arithmetic mean was calculated for each sample. This mean represents the direction of local flow.

COLOURED PICTURES
Images en couleur

Figure 2.9 The horizontal shelf cut into the section reveals the cross-stratification traces

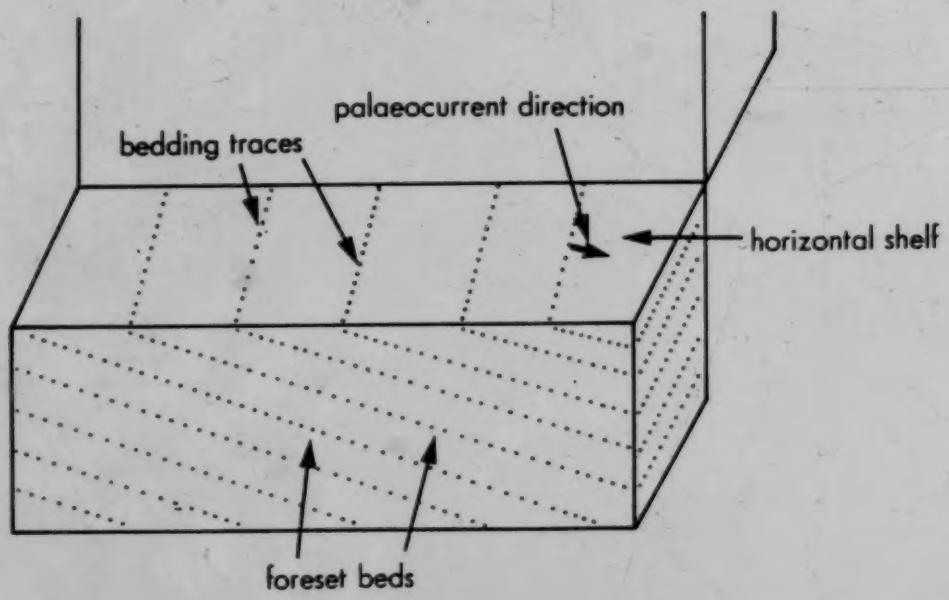


Figure 2.10 Palaeocurrent measurement

3. MORAINIC LANDFORMS AND TILLS/DIAMICTONS

3.1 Introduction

The term *moraine* was originally applied in the late eighteenth century to *rubble heaps* observed in the French Alps (Lucas and Howarth, 1979). It was not until 1841, when Charpentier introduced this term into the scientific literature, that it was accepted (German, 1968). By definition a moraine is a depositional landform consisting generally of till, although stratified sediments may also be incorporated. The general term is now used exclusively as a landform descriptive term.

3.1.1 Classification

Numerous researchers in glacial geomorphology have outlined classifications of morainic landforms (e.g. Chamberlin, 1895; Prest, 1968; Price, 1973; Goldthwait, 1975; Sugden and John, 1976; Aario, 1977; Lucas and Howarth, 1979; Kurimo, 1980; Kemmis *et al.*, 1981). These classifications are all morphogenetic and thus certain assumptions are implicit. It has often been assumed, with a logical basis, that two particular landforms with similar morphologic expressions would share the same genesis. However, with improved methodology and increased knowledge of glacial sedimentation more refined interpretations of complex landform evolution are now possible (Kurimo *et al.*, 1981). No longer can the broad assumption be made that landforms of similar appearance share the same genesis, even within a small area. Realization of this point has complicated the classification of morainic landforms. Therefore, the vast arrays of actual sizes, shapes and compositional materials are largely responsible for the multitude of names in the literature for morainic landforms of somewhat similar appearances.

Aario (1977, p. 98) suggested that "classification and terminology are primary tools in geological communication, not an end in themselves". Yet, if precision of description and interpretation is a goal, classification and standardized terminology are necessary. Thus criteria for landform recognition and description must be selected.

These criteria include;

a. – morphologic character (e.g. ridge, hummock, ring formation, plateau)

b. – dominant process(es) leading to the formation of the morainic landforms (observed, interpreted)

c. – place of deposition relative to the ice margin (marginal, supramarginal, inframarginal) or relative to ice lobes (interlobate, intralobate)

d. – contact of the moraine with glacier ice (active, inactive)

e. – position of deposition relative to the vertical ice division (superglacial, englacial, subglacial)

f. – orientation of the morainic landforms relative to the direction of assumed ice flow (parallel, transverse, oblique, non–directional) or the arrangement and pattern of the features (grouped, isolated, transitional)

g. – sedimentological and structural characteristics of the compositional material

Because the classification of moraines embraces a vast literature a review of selected material, which is most relevant to predominant landforms of the study area, follows.

3.2 Hummocky Moraine

Hummocky moraine is a descriptive and collective term for a broad range of landforms (Table 3.1), many of which display little distinct pattern, orientation or uniform morphology. Often referred to as *knob and kettle topography* tracts of these landforms may have considerable areal extent, being located in former marginal or inframarginal areas. It is almost certain that these landforms are polygenetic and thus subdivision on the basis of dominant formation processes is a logical means of differentiation.

(A) LANDFORM

MORAINE RIDGE

A moraine ridge is any ridge form, composed predominantly of till with possible additions of sand and gravel lenses. These linear ridges are distinguished from "rim ridges" or "ring ridges" which encircle and are part of, moraine plateaux or prairie mounds respectively. Moraine ridges are often steep-sided and vary greatly in height, length and plan form. Sometimes they intersect at acute angles or are superimposed upon each other. Aligned ridges (transverse or parallel) are usually asymmetrical in form.

(B) ASSOCIATION WITH OTHER HUMMOCKY MORAINE LANDFORMS

(C) OCCURRENCE

(D) SYNONYMS

1.1 within hummocky moraine zones		1.2 transitional to hummocky moraine	
1.1.1 random orientation		1.2.1 transverse orientation	1.2.2 parallel orientation
1.1.1.1	"disintegration ridge"	1.2.1.1 "transverse ridge"	1.2.2.1 "drumlinoid ridge"
1.1.1.2	"linear disintegration ridge"	1.2.1.2 "Hog's back moraine ridge"	
1.1.1.3	"linear till disintegration ridge"	1.2.1.3 "ribbed moraine ridge"	
1.1.1.4	"ice-contact disintegration ridge"	1.2.1.4 "Rogen ridge"	
1.1.1.5	"dump ridge"	1.2.1.5 "washboard ridge"	
1.1.1.6	"crevasse-filling"		
1.1.1.7	"ice-crack ridge"		
1.1.1.8	"till and till-cored esker"		

(continued)

Table 3.1 Four primary landforms of hummocky moraine complexes

(A) LANDFORM	PRAIRIE MOUND		
	A prairie mound is composed typically of a till ring ridge around a central depression. The central depression frequently contains lacustrine sediments to a level slightly above the intermound depression. The ring ridge's inner slope is usually less steep than the outer slope and the ridge has a relatively consistent height around the central depression. This ring ridge is commonly breached in one or more positions. Prairie mounds are, on average 180 metres in diameter with rim heights up to 3 metres. Their randomly spaced occurrence within "fields" is the rule as few isolated prairie mounds are found. Density of prairie mounds within fields varies considerably but may average 35 to 60 mounds per square kilometre.		
(B) ASSOCIATION WITH OTHER HUMMOCKY MORAINE LANDFORMS	2.1	outside hummocky moraine zones	2.2 within hummocky moraine zones
(C) OCCURRENCE	2.1.1	fields/non-oriented	2.2.1 fields/non-oriented
(D) SYNONYMS	2.1.1.1	"doughnuts"	2.2.1.1 "rimmed kettles"
	2.1.1.2	"humpies"	2.2.1.2 "closed disintegration ridges"
	2.1.1.3	"till and silt mounds"	2.2.1.3 "circular disintegration ridges"
	2.1.1.4	"pingo scars"	2.2.1.4 "ring ridges"
	2.1.1.5	"plains plateau"	2.2.1.5 "rim ridges"
			2.2.1.6 "ice block ridges"
			2.2.1.7 "ice-contact rings"

(continued)

Table 3.1 (continued) Four primary landforms of hummocky moraine complexes

	MORAINE PLATEAU	MORAINE HUMMOCK
(A) LANDFORM	Moraine plateaux often form the only level tracts of land within an otherwise rugged hummocky moraine topography. In ideal situations they appear as true plateaux with irregularly outlined, flat-topped surfaces projecting upward to the same level as the adjacent hummocks. Often completely surrounded by a till rim ridge slightly above the level portion, the central surface is commonly underlain by water deposited sediments. The outside rim slopes are steep, although gentle to non-existent in the interior. The size of these plateaux is varied, with diameters up to 7 kilometres. The smaller plateaux range down to a few hundred metres across and are usually circular.	Hummocks are conical shaped hills within hummocky moraine zones, often referred to as knobs (knob and kettle topography). They are composed primarily of till but often have water deposited sediments included. There are no guidelines set for their maximum size or shape, and their distribution is random and non-oriented.
(B) ASSOCIATION WITH OTHER HUMMOCKY MORAINE LANDFORMS	3.1 within hummocky moraine zones	4.1 within hummocky moraine zones
(C) OCCURRENCE	3.1.1 isolated/non-oriented	4.1.1 random orientation and distribution
(D) SYNONYMS	3.1.1.1 "rim ringed moraine lake plateaux" 3.1.1.2 "rim ringed saucer-shaped perched lacustrine plain" 3.1.1.3 "rim ringed ice-contact lacustrine topography" 3.1.1.4 "rim ringed elevated lake plain" 3.1.1.5 "rim ringed ice-restricted lake plain" 3.1.1.6 "rim ringed ice-walled lake plain"	4.1.1.1 "knobs" 4.1.1.2 "hills" 4.1.1.3 "hillocks" 4.1.1.4 "mounds"

Table 3.1 (continued) Four primary landforms of hummocky moraine complexes

3.2.1 Formation Theories; A Critical Review

There are five basic formation theories for the dominant landforms typical of hummocky moraine zones (Table 3.2). Aario (1977) suggested that hummocky moraine should be subdivided into hummocky *disintegration* moraine, hummocky *squeezed-up* moraine, and hummocky *active ice* moraine. However, other authors might want to expand this further to include ice diapirism processes (e.g. Minell, 1979) and periglacial processes (e.g. Bik, 1967, 1968, 1969; Flemal, 1972; Seppala, 1972). Many authors have preferred to use combinations of the basic formation processes (e.g. Gravenor and Kupsch, 1959; Parizek, 1969; Minell, 1979) in order to approach an acceptable, general theory (Table 3.2). In addition, Kemmis *et al.*, (1981) recognized that these landforms may evolve with time-transgressive changes in processes.

3.2.1.1 The Let-Down Theory

The let-down theory proposed by Gravenor (1955) has three requirements; marginal stagnation of the ice mass, widespread distribution of varied superglacial deposits, and differential ablation of the underlying ice. The development of an uneven surface on the stagnant ice is essential and this follows from the above requirements.

Ice stagnation may occur as ice thins during amelioration. Alternatively, stagnation may be induced by topographic conditions. A topographic high may cause proximal compression and, if not followed by large scale extension, debris-bearing ice may stagnate (Minell, 1979). Finally, stagnation need not be *en masse* but rather, progressive stagnation along a narrow marginal zone may occur because of insulating superglacial drift (Clayton, 1967).

Central to the discussion is the requirement for large amounts of superglacial debris to be distributed over the surface in a heterogeneous manner. Gravenor (1955) assumed that this considerable thickness was attained strictly through the ablational process. Several mechanisms by which superglacial debris was carried to the surface from the basal areas of the ice mass prior to, or during, the ablation of the ice mass have been suggested. Clayton (1964) and Boulton (1967) noted that subglacial debris was carried up to the surface along shear planes in active ice. Clayton (1967) expanded this

FORMATION THEORY	LANDFORMS STUDIED	LOCATION	REFERENCE
1. "Let-Down"	prairie mounds	Western Canada prairies	Gravenor (1955)
	selected hummocky moraine forms	Alaska; Missouri Coteau	Clayton (1964, 1967)
	ice-walled lakes	Missouri Coteau	Clayton and Cherry (1967)
	selected hummocky moraine forms	Spitsbergen	Boulton (1972)
	hummocks	Finland	Aartolahti (1974, 1975)
	ridges and hummocks	Finland	Kurimo (1977)
2. "Ice-Press"	ridges and plateaux	Sweden	Hoppe (1952, 1957)
	all hummocky moraine forms	Alberta	Stalker (1960)
3." "Active Ice"	Rogen moraine	Sweden	Lundquist (1969)
	Rogen and Blattnick moraine	Sweden	Markgren and Lassila (1980)
	Rogen moraine	Sweden	Shaw (1979)
	glacial thrust blocks	Canadian and U.S. prairies	Moran et al., (1980)
	ribbed moraine	Quebec	Bouchard (1980)
4. "Periglacial"	till and silt mounds	Alberta	Henderson (1952)
	mounds	British Columbia	Mathews (1963)
	prairie mounds	Alberta	Bik (1967, 1968, 1969)
	collapsed pingos	Finland	Seppala (1972)
	De Kalb mounds	Illinois	Flemal (1972, 1976)
	De Kalb mounds	Illinois	Flemal et al., (1973)
5. "Ice Diapirism"	moraine plateaux	Lappland	Minell (1979)
combined 1 & 2	all hummocky moraine forms	Western Canada	Gravenor and Kupsch (1959)
combined 1 & 2	selected hummocky moraine forms	Interior North America	Winters (1960)
combined 1 & 2	selected hummocky moraine forms	Saskatchewan	Parizek (1969)
combined 1 & 3	selected hummocky moraine forms	Interior North America	Clayton and Moran (1974)
combined 1 & 3	all hummocky moraine forms	Iowa	Kemmis et al., (1981)
combined 1, 2 & 3	transverse ridges	Sweden	Minell (1977)
combined 1, 2 & 3	all hummocky moraine forms	Finland	Aario (1977)
combined 1, 2, 3, & 5	all hummocky moraine forms	Lappland	Minell (1979)

Table 3.2 Theories of hummocky moraine formation

statement by suggesting that such thrusting occurs in zones of extreme compressive flow. Boulton (1967) noted that in zones of compressive flow subglacial debris, frozen onto the base of the glacier, is delivered to the surface as the flow lines turn upward at the frontal margin or the glacier. The exposure of steeply dipping debris bands as glacier ice ablates has been observed by Boulton (1967) in the frontal stagnant zone of Sorbreen, Spitsbergen. The debris *dykes*, originally frozen, thaw slowly and the material (because of its fluidity) spreads over the glacier surface and accumulates in hollows.

The essential, uneven, surface configuration is predominantly controlled by differential ablation (Gravenor, 1955). Differential ablation of ice below a heterogeneous debris layer takes place as areas with a thick mantle ablate much more slowly than those with a thin cover. Hence, depressions may form simply from an unequal debris distribution. Alternatively, depressions may form as subglacial caves collapse (Clayton, 1964), by the formation of superglacial thaw lakes (Eyles, 1979) or as the result of increased rates of melting along crevasses. Whatever the creation processes), these depressions, once formed become collection areas into which adjacent materials may move by superglacial wash (Gravenor, 1955), or by mass movement accompanying backwasting (Boulton, 1967; Eyles, 1979). The newly acquired debris within these pits now inhibits the melting of the supporting ice and the high areas, from which the debris was removed, become subject to increased ablation. Thus, an inversion process proceeds and the final configuration of the landscape is that attained when the drift cover comes to rest on the underlying ground surface.

Should an ice core remain within the mound during the final stages of ablation a central depression may develop when this core eventually melts out. Where such a central depression exists a prairie mound usually results. Differential ablation in the ice mass, partly inherited from active ice structures (e.g. crevasses), may provide conditions in which *controlled* linear features may develop (Gravenor and Kupsch, 1959; Clayton, 1967).

The let-down theory has been criticized because of a number of inconsistencies. For example, Bik (1969) noted that ridges formed by these processes should be of low angle and elevation due to the fluid nature of the material. Bik (1969) also felt that Gravenor's (1955) hypothesis was unlikely because a specific set of climatic conditions,

plus critical thickness and albedo values for both the ice and debris cover, were essential for relief inversion to occur. Also, the relief inversion process should have happened repestedly. Furthermore, if a number of inversions did take place debris would distribute rather than concentrate in a mound form.

The formation of till in terms of this relief inversion hypothesis essentially involves a redistribution of debris in the superglacial environment and a passive, *in situ* let-down for deposition. However, Bik (1969) and Seppala (1972) both noted that till did not strictly exhibit these characteristics. Bik (1969) stated that till in the rims of prairie mounds he investigated was indistinguishable from the presumably *basal* till in the intermound depressions. Seppala (1972) commented on the existence of distinct fabric maxima and the presence of tight packing in the till. Seppala (1972) also pointed out that he could find no evidence of wash structures in the forms that he examined.

Boulton (1972, 1975, 1976), although not directing his comments towards work of the previous authors, provided solutions to many of these apparent contradictions. Boulton (1972) stated that flow material may show distinct orientations in fabric and an absence of wash structures if the related flow was slow. Fabrics perpendicular to the orientation of linear let-down features might be expected. Boulton (1975, 1976) also suggested that secondary effects, such as desiccation, may produce densities and preconsolidation values in flow till similar to those of lodgement till. Finally, prairie mounds formed completely of lacustrine silts have been described (Mathews, 1963) and these could not possibly have formed by the let-down mechanism.

3.2.1.2 The Ice-press Theory

The subglacial, ice-press theory was originally explained in detail by Hoppe (1952) and expanded by Stalker (1960). Gravenor and Kupsch (1959) and Parizek (1969) accepted the theory but recognized some inherent deficiencies and problems. Stalker (1960, p. 18) explained the ice-press process as follows:

> " During deglaciation crevasses and holes of various types were present in the base of the ice. At the same time the sub-ice material, generally till but in places bedrock or other material, was either not frozen or only partly frozen. It also contained much water, commonly being completely saturated, and thus was in a highly plastic or a fluid condition. The weight of ice on this plastic material pressed it towards the crevasses and holes, increasing the amount of

> material there while decreasing the amount beneath the ice. In large holes most of the pressed material came to rest around their margins and only a little near the centre. When the ice finally melted the material that had been pressed into the crevasses and holes stood as ridges, whereas the places from which material had been pressed were low and commonly formed troughs and dead-ice hollows alongside the ice-pressed ridges.".

The sub-ice material must be either pressed in below the ridge that is being constructed, raising it bodily or by plastering over the surface of the ridge so increasing its height. Theoretically, the ridge should have *grown* until the supply of plastic material was exhausted, the ice margin had melted back from the ridge, or the ridge form had reached an equilibrium height with respect to the physical pressure exerted (Stalker, 1960).

The ice-press theory was invoked in an attempt to explain some fundamental internal characteristics of till ridges within hummocky moraine zones. Hoppe's (1952) observations (in Sweden) of a compact till which was completely unsorted, with no evidence of washing, led to the conclusion that it was a basal till. This deduction was reiterated by Stalker (1960) for similar forms in Alberta. Hoppe (1952) stressed the distinctive till fabric exhibited at various sectors within the ridges. Long axes of pebbles were preferentially oriented at right angles to the long dimension of the ridge. This suggested movement of till outward from the dead-ice hollows towards the ridges. This marked preferred orientation of coarse clasts was assumed to be contrary to expected random pebble orientations resulting from material falling or sliding into a crevasse or depression in the ice. Stalker (1960) extended these characteristics to include a consistent association between the relief forms and dead-ice hollows. He also noted that some water-deposited sediments were associated with most of the ridges as either centre fillings or pockets within the ridge materials.

The conclusion that "pressing of till into crevasses and holes is the only process that could form ridges of basal, unsorted till with a regular orientation of stones" (Stalker, 1960, p. 19) has been challenged with regard to each of the above diagnostic characteristics. Gravenor and Kupsch (1959) were the first to criticize Hoppe's (1952) deductions. They suggested that the compact nature of the till need not indicate a subglacial origin of the landform as it could have been inherited from the original texture

and structure and preserved during slow melting and let-down. Boulton (1972) also stated that two basic subdivisions of flow till may develop supraglacially; an upper, washed and crudely stratified till (allochtonous flow till) and a lower, massive element which has not been exposed to the atmosphere (parautochtonous flow till). Thus, this lower, buried, till does not undergo sorting, as Stalker (1960) suggested, even during subsequent slow flow (Boulton, 1972). Secondly, Hoppe's (1952) observed fabrics could have resulted from lateral outward flow of the plastic material as debris moved down a stagnant ice block surface (Gravenor and Kupsch, 1959).

If the squeeze mechanism is to be accepted a number of requirements must be met: a. Subglacial cavities must open up and remain open long enough to allow material to be squeezed in laterally from below. To maintain open basal cavities the overlying ice must be thin or stagnant so as not to close them by plastic deformation. Such cavity-maintenance has always been considered a problem as workers on subglacial and englacial eskers explain (see Shaw, 1971; Shreve, 1972). Subglacial cavity development results from enlargement of crevasses and/or meltwater channels (Stalker, 1960). However, even Stalker (1960, p. 20) stated that "indeed no process can be suggested to explain the existence of large holes ... that were necessary for the formation of the large moraine plateaux".

b. The ice-press concept presupposes that hummocky moraine features were mainly constructed by the weight of ice pressing on underlying, saturated materials. Stalker (1960) calculated, using simple density associations (Equation 3.1) of overlying ice and subglacial material, that ice thicknesses in the continental glaciers could have been sufficient to exert the pressure necessary to raise material high up into the basal cavities:

ice thickness x ice density = till density x ridge height (Equation 3.1)

However, this approach appears to be much too simplistic. The normal pressure exerted by the ice on the fluid material would be equally distributed and thus no point pressure exerted. Some material would probably be

squeezed but, intuitively, it seems not to the extent Stalker (1960) suggested. The amount of squeezing would also decrease with time as material thinned beneath the ice sheet and the ridge grew.

The ice-press theory may be a plausible explanation of small ridge features as described by Hoppe (1952) but many criticisms have been levelled against it. It is not likely to explain all hummocky moraine landforms. Stalker's (1960) extension of the ice-press hypothesis to include larger landforms, such as moraine plateaux, is very questionable. The occurrence of basal cavities of such proportion to contain these large landforms seems unlikely. Indeed Stalker (1960) stated that he could provide no mechanism for the development and maintenance of such large holes. Secondly, the requirement of a large amount of highly plastic, basal material would demand a substantial collection area and thus a long distance of movement. Thirdly, ice thicknesses would need to be very great to provide the pressure to displace the large quantities of material. Finally, if the sub-ice material was readily available and in a highly plastic state, and pressures were significant enough to move this material, it would probably distribute itself equally within the large cavity instead of forming a ridge around the perimeter.

Even if all of the critical conditions were met, whereby dense, quasi-plastic or fluid materials were squeezed into ice-walled basal cavities, the problem still remains to account for the preservation of the form as the supporting and pressure-supplying ice ablated around it. Since meltwater from continued ablation should still have been readily available the material would have had little chance to dry and thus change its viscosity or cohesion. Particularly where the squeezed material had been raised to a great height, readjustment would have been expected in the form of reverse flows during late stages of deglaciation.

Both Hoppe (1952) and Stalker (1960) suggested that continental ice was relatively clean and that hummocky moraine features were thus largely the result of squeezing-up of subglacial debris into basal cavities. However, Weertman (1966) has suggested that continental glaciers should have contained thick zones of englacial debris. This englacial debris may have moved into superglacial positions in zones of compressive flow or marginal thrusting during active ice conditions. Also, following local ice stagnation,

continued surface ablation should have left this englacial debris as a thick superglacial mantle. Much evidence exists for thick superglacial deposits associated with the late Wisconsinan ice sheets. In this regard Clayton (1967) lists three points for one region in North America:

a. the contorted, folded and faulted bedding of collapsed stream deposits and lake sediments indicate that the deposits accumulated on stagnant ice. A similar topography of morainic deposits is evidence for a similar formation mode of these features; collapse of superglacial till as the stagnant ice melted.

b. the superglacial debris insulated the underlying ice and thus buried ice persisted on the Missouri Coteau for at least 3,000 years. This long time-span is based upon radiocarbon dates on organic materials and mollusc shells.

c. the materials which were radiocarbon dated (spruce trees, molluscs etc.) indicated that a temperate climate existed for those 3,000 years. A favourable, superglacial environment for these fauna and flora could be provided only if the buried ice was well insulated by a thick superglacial mantle of debris.

Gravenor and Kupsch (1959) have observed superimposed junctions of two disintegration ridges and disintegration ridges superimposed upon *active-ice* features, such as drumlins and flutings. These observations provide additional arguments against a squeezing theory and favour a let-down of material with no disturbance of the underlying ridge form.

Extrapolation of processes observed on modern glaciers to Pleistocene glaciers is common. Boulton (1967) stated that observations at the margin of Sorbreen, Spitsbergen, deny the conditions under which plastic material could be forced up into basal cavities. Although the material at the base of the glacier may be wet, it is often frozen when contained within debris bands. Also, Boulton (1967, p. 722) translated work done by Gripp (1929) on modern glaciers in Spitsbergen where he stated " nowhere have we seen subglacial ice-free moraine, or ground moraine *senso stricto* ".

Bik (1967, 1968, 1969), a strong supporter of a periglacial origin for prairie mounds presented several arguments against the ice-press theory. Bik (1969, p. 99)

stated that the ice-press theory " ... explains neither the breaching of the rim nor the central depression of the mounds, both of which were found to be a part of the parent forms of present-day mounds ...". Furthermore, prairie mound fields often occur in isolation and are not directly associated with other hummocky moraine features. It seems unlikely that the squeeze-up mechanism was responsible for their formation since a field of only circular or oval-shaped cavities would have had to open up. Finally, the ice-press theory can not be applied to prairie mounds composed completely of proglacial sediments. For example, Mathews (1963) suggested that formation of these prairie mounds must have occurred after the disappearance of glacier ice from their location because the mounds overlie and incorporate glaciolacustrine sediments (of Glacial Lake Peace).

3.2.1.3 **The Active Ice Theory**

The term *hummocky active ice moraine* has been applied to some hummocky moraine landforms. For these landforms active ice processes are essential, at least in the initial stages of formation. Hoppe (1952, 1957) included the Veikki moraine of Sweden in this class because shear planes were common in the related tills. He referred to the Veikki moraine as a "hummocky moraine landscape associated with active ice". Kuujansu (1967, Aartolahti, 1974) included the Pulju moraine of the Finnish Lapland in this class. Because a subglacial squeeze origin was suggested this moraine could have been included in either the hummocky squeezed-up moraine or hummocky active-ice moraine classes.

Lundquist (1969) discussed hummocky active-ice moraines in connection with Rogen moraine landforms. This type, and its Canadian Shield counterpart - ribbed moraine (Bouchard, 1980), has been given much attention in Sweden, Finland and Canada. Rogen moraine, a special type of transverse moraine, is of particular interest in light of its transitional association with drumlins and flutings (Aario, 1977; Shaw, 1979). Lundquist (1969) noted small-scale flutings superimposed on Rogen moraine surfaces and Bouchard (1980) showed that this could be anticipated. Aario (1977, p. 91) stated that "Rogen hummocks" were composed of "mainly basal till, although the upper parts may be of ablation till. The layered horizons with much sorted material are also common.". Shaw (1979) explained that the internal structure of the ridges showed folded till bodies

dislocated by thrust planes. Pebble fabrics showed no preferred two-dimensional orientation, but the dip of the pebbles was found to be conformable to the tectonic structure.

Although at least a dozen theories of origin exist for Rogen moraine (Bouchard, 1980) some agreement can be seen in the recent literature. Of particular note is the concept of their subglacial formation by active ice in depressional areas of former compressive or retarded flow. This is illustrated by evidence of thrusting, folding and stacking of debris (Minell, 1977; Shaw, 1979; Bouchard, 1980; Markgren and Lassila, 1980). Shaw (1979) and Bouchard (1980) noted that slow basal melt-out, following ice stagnation, allowed explanation of the formation and preservation of discrete layers of sorted sediment lying horizontally and cross-cutting tectonic structures. However, Bouchard (1980) stated that the permafrost requirement, as set out by Shaw (1979), need not be invoked. Other factors such as the thickness of the overlying stagnant ice and the amount of debris in this ice could insulate the basal part from surface influences.

3.2.1.4 **The Periglacial Theories**

Numerous periglacial theories have been used to explain the formation of certain hummocky moraine features; prairie mounds (Henderson, 1952; Mathews, 1963; Bik, 1967, 1968, 1969; Flemel, 1976), elliptical hillocks (Flemel, 1972; Flemel *et al.*, 1973) and circular, semi-circular and elongate till ridges (Seppala, 1972). Other studies have dealt with collapsed pingos, features which often are not easily differentiated from landforms created by glacial processes (e.g. Watson and Watson, 1972; Flemel, 1976).

The periglacial theories attempted to explain how/why morphologically identical landforms, in close proximity, developed on widely different parent materials. The glacigenic hypotheses were considered improbable and therefore deformation of a pre-existing deposit was suggested (Bik, 1969). Finally, morphologically similar landforms, particularly those described in the European literature, have been shown to be collapsed pingo remnants (Seppala, 1972; Watson and Watson, 1972). Several periglacial hypotheses are presented below.

Ice Wedge Hypothesis:

Henderson (1952) invoked a periglacial origin for prairie mounds in the Sturgeon Lake area, Alberta. The proposed mechanism required that the centres of giant ice wedge polygons be bulged upwards in response to lateral pressures exerted by the growth of the wedges. Within the raised, central portion of each polygon a core of segregated ice developed. The central depression of the prairie mound evolved later as this ice core melted, breaches in the rim allowing the water to drain away.

This hypothesis has been rejected both by proponents of glacial theories and other periglacial theories. Gravenor (1955) pointed out that the theory was improbable from the standpoint of the size requirements of the ice wedges and that evidence of ice wedging is lacking in many areas of hummocky moraine. Mathews (1963) stated that this hypothesis will not explain the occurrence of isolated mounds. Bik (1969) stated that the distribution of prairie mounds tends to be random and not equidistant as requisite to the theory. Also sharing of mound rims and composite mounds clearly cannot be explained by this ice wedge theory. Finally, no modern analogues exist for this hypothesis in widespread permafrost environments.

Collapsed Pingo Hypotheses:

Mathews (1963), Bik (1967, 1968, 1969), Flemel (1972), Seppala (1972) and Flemel *et al*., (1973) have all invoked a modified, collapsed pingo mechanism for prairie mounds. Mathews (1963, p. 18) suggested that the development of prairie mounds composed of Glacial Lake Peace sediments near Fort St. John, British Columbia,

> "possibly involved displacement of water saturated soil, rather than water alone, during the development of permafrost, and that this soil moved at depth towards points of potential rupture, where permafrost was thinnest, as for example beneath the center of shallow ponds".

The mechanism of mounding by segregation of an ice core not only accounts for the variety of parent materials, the characteristic central depression and rim breaches, but it also explains the distribution of mounds within a *field* and the apparent control of elevations for the *fields* themselves.

Bik (1969), in a detailed comparison of collapsed pingos in Europe and prairie mounds in southern Alberta, suggested that a number of similarities exist in their forms. Because of this similarity, and the array of materials which comprise prairie mounds, a similar mechanism was suggested. Bik (1969) outlined a *closed system* method of formation where mobile, saturated material was sandwiched between an aggrading permafrost layer and a subsurface fossil permafrost layer or bedrock surface. As pressure increased, with the developing permafrost, an eruption of this supersaturated material occurred as it flowed into areas of low stress. This mechanism is therefore somewhat comparable to the ice-press mechanism, but involves ground ice rather than glacial ice stresses. These eruption sites presumably occurred at points of weakness in the aggrading permafrost layer, usually in depressions. Beneath the mound (where the eruption had occurred) the release of pressure allowed water to freeze and the development of a segregated ice core. The breaches in the ring wall of the prairie mound resulted from radial cracks in the mound caused by the growth of this ice core beneath it. Final melting of the clear ice core left the central depression and likely this would have accentuated the crack by drainage, leaving the commonly breached form.

This mechanism has several requirements. Bik (1969, p. 104) went to great lengths to answer the following questions that he himself had posed;

a. "Can till be displaced below the surface under an aggrading permafrost layer, as suggested by Mathews (1963) for lacustrine deposits?
b. Can discrete ice cores be segregated in till?
c. What controls the distribution of prairie mound fields, which appear to be of limited vertical and rather unlimited lateral extent?"

Displacement of till is essential to the hypothesis as an excess of material was noted in prairie mound rims. This contrasts to observations on European collapsed pingos where the volume of material in their rings walls was approximately equal to the volume of the central depression. The excess material in prairie mound rims was therefore assumed to have originated in the intermound depressions. The liquid limit of the till sampled from the mounds studied by Bik (1968) was low, as was the plasticity index. Thus rather high mobility under saturated or supersaturated conditions might be expected (Bik, 1969). He

drew examples from collapsed pingos in Europe to show the wide range of materials, including till, in which they formed. Using this as evidence Bik (1969, p. 110) stated that

> " ... though permeability of till on which the mounds formed is undoubtedly low, this does not in itself exclude an explanation of prairie mounds as resulting from some form of pingo formation ...".

The forces that formed the protrusion in the mound development were derived from the process of permafrost aggradation. Bik (1969) suggested that, where the initial landscape was undulating, permafrost development proceeded much more quickly over initially high areas. Thus, the development of the mounds would occur in depressions with till displacement directed towards points rather than lines of weakness in the frozen layer. Continued subsurface displacement, as permafrost aggradation progressed, would eventually lead to relief inversion. Beneath the aggrading permafrost layer a segregated ice core would develop. Ice segregation would start earlier and persist longer below the depressions than beneath the convexities of the initial relief (Bik, 1969). This is due to greater porewater pressure gradients towards the penetrating frost below the initial depressions.

The point relating to prairie mound distributions is interesting. Bik (1969) noted that within western Canada mound fields are controlled features in terms of elevation. They occur generally in belts that bend upstream into major river valleys, mark the former extent of proglacial lakes or, sometimes encircle higher tracts of terrain. The implications of this for development are twofold. The availability of moisture and the possibility of a closed system being developed must have been controlled to a large extent by elevation. Establishment of the relict permafrost was probably prior to the proglacial lake development as a direct result of climatic cooling (Bik, 1969). Inundation of areas with water would cause increased melting of the underlying permafrost from the top downwards. As these lakes receded re-establishment of permafrost in the shore zones would set up the conditions necessary for closed system development. This is not unlike Mackay's (1979) hypothetical sequence of events for closed-system pingo development on the Mackenzie Delta, Northwest Territories.

Bik's (1967, 1968, 1969) theory has much merit for those prairie mounds occurring in fields which are isolated and not in close association with other hummocky

moraine features. Certain requirements of the theory, such as relict permafrost (or bedrock) and aggrading permafrost sandwiching a supersaturated layer, are critical and perhaps hard to attain. Bik (1969) explained that the availability of an unfrozen, supersaturated layer below an aggrading permafrost was a winter condition. Subsurface displacement of materials towards areas of weakness in the frozen overburden was considered to be a summer condition. However, the theory requires that these conditions be met at the same time. Finally, there is little evidence for permafrost aggradation immediately following the partial drainage of the glacial lakes in western Canada.

Flemel (1972) offered a similar mechanism for the formation of the De Kalb mounds of north-central Illinois, but in this case an *open system* pingo analogy was suggested. He stated that these mounds formed in close proximity to the former glacier margin. Flemel (1972) made the assumption that permafrost had initially developed along the margin of the ice sheet. The ice sheet promoted groundwater flow from beneath the glacier towards the margin and this flow was dependent upon the degree of ice melting and the hydraulic head created by the glacier. Proglacially, this groundwater was confined by the rigid permafrost layer which buckled upwards at points of weakness as the hydrostatic pressure increased. Zones of weakness may have occurred under shallow pools of water. At this stage the bulge could have ruptured or, more probably, the groundwater froze to produce an ice lens as pressure was released. Surficial melting of the ice lens, and continued artesian force from below, led to the development of passages through which both water and material could be ejected. Successive accretion of material resulted in the development of mounds. Transfer of materials from beneath the mounds into the ponds produced some subsidence of the subjacent ground surface. In the final stages a circular mound of sediments remained with an ice core. Eventual melting of the core left the prairie mound form.

Seppala (1972) described till mounds in the Finnish Laplands and attributed their formation to the collapse of open system pingos. In Lapland these pingos formed preferentially in poorly drained basins which were particularly conducive to permafrost and hydrostatic pressure development (Seppala, 1972).

3.2.1.5 **The Ice Diapirism Theory**

This newest theory (Minell, 1979) is based on experimental results of Ramberg (1967) and Berner *et al.*, (1972). Minell (1979) suggested that prairie mound and moraine plateau formation could be explained as the doming of material, or as the rising of dykes of relatively clean ice between blocks of till by diapirism. Central to the diapirism theory is the unstable condition whereby strata consisting of lighter layers (clean ice) are overlain by denser, heavier layers (debris–rich bands). Given this condition the lighter layer will move upward, taking on a dome form, and the heavier layer will sink (Ramberg, 1967). Ramberg (1967) in model experiments showed that, with a uniform overburden thickness, the thickness of the underlying material determined the scale and spacing of doming. Further, differences in density and viscosity between the two layers will influence the scale of doming (Berner *et al.*, 1972; Minell, 1979). The ultimate form of the dome is dependent upon the viscosity differences between the two layers (Berner *et al.*, 1972). If the covering layer has a much lower viscosity than the underlying layer the growing domes will become broader while the sinking, softer medium will form thin narrow basins, and *vice versa* (Minell, 1979). He stated that for this unstable condition to occur large amounts of englacial or superglacial debris over relatively clean ice must be explained. He suggested that compressive flow, due to retarded ice movement over a topographic *high*, could provide the material accumulation in the upper parts of the ice mass.

To explain the formation of prairie mounds and moraine plateaux Minell (1979) suggested that two forms of diapiric structures might occur. Simple diapiric doming through material could be implied for the smaller forms or, a block of overburden could be held between two clean–ice diapirs. As the containing ice walls melted and collapsed a block of till would remain.

Although diapiric structures are well documented (e.g. salt domes) and diapiric theory has considerable geotechnical support, the optimum conditions necessary for extrapolation into the glacial ice/debris mixture realm seem unlikely. While it is certainly possible that an isolated diapir may form, the critical condition of a continuous, high density mantle of debris on the glacier surface is unlikely, especially in light of work done by Boulton (1972) who stated that an irregular debris distribution is the rule. Minell (1979),

agreed that many hummocky moraine features, in the vicinity of the moraine plateaux which he described, developed primarily through ablation, but he should not have suggested that this diapiric model could explain features so closely related in space. Even if the situation existed where all of the critical conditions were met for diapirism, on the scale Minell (1979) suggested, it is difficult to apply a model which uses two-dimensional wavelengths between the two adjacent diapirs to circular forms.

3.3 Morainic Landforms and Tills/Diamictons of the Study Area; Observations and Interpretations

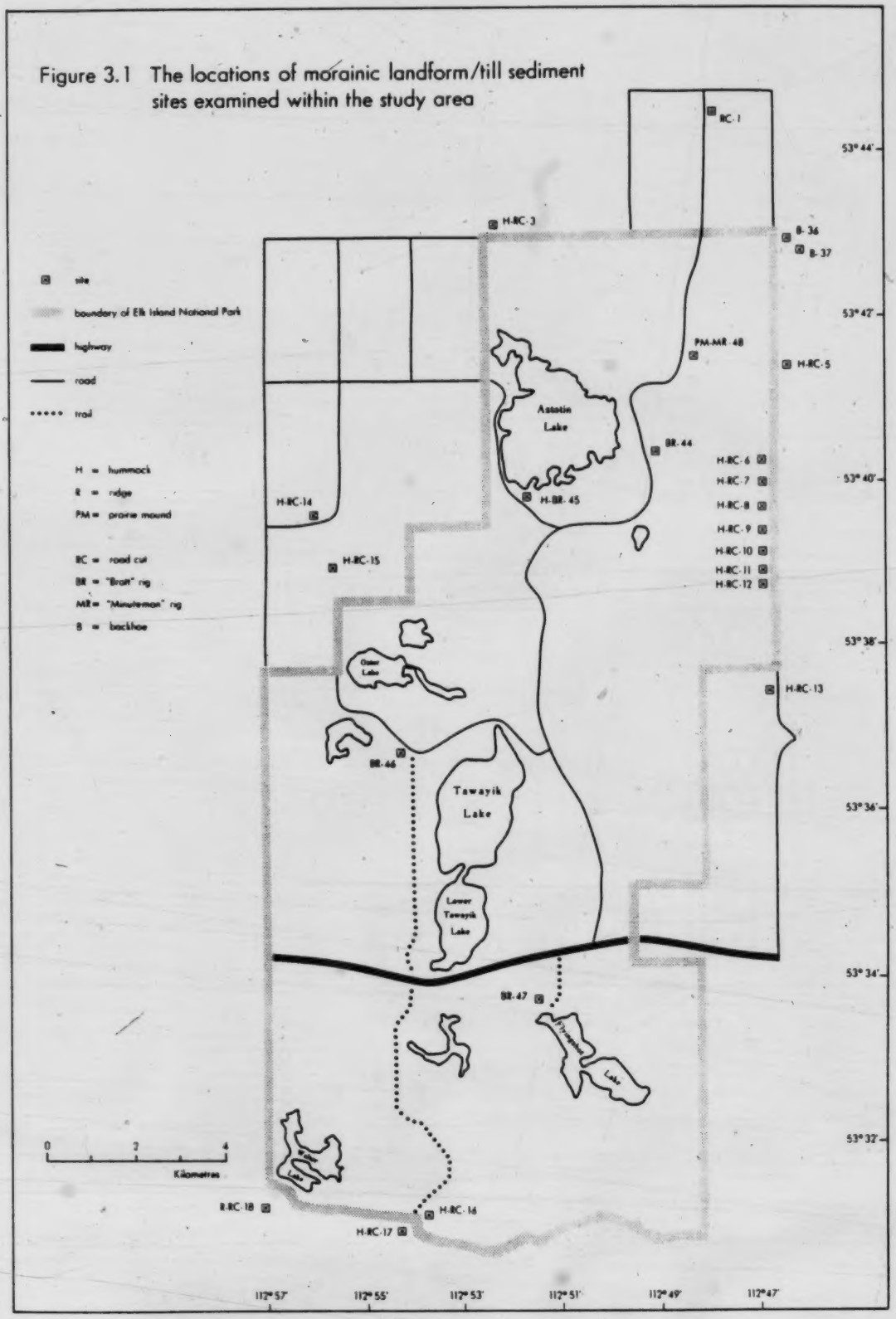
3.3.1 Introduction

Aerial photograph interpretation and field reconnaissance disclosed a variety of morainic landforms, each characteristic of hummocky moraine tracts. Hummocks, ridges and prairie mounds (with associated intervening depressions) dominate the physiographic setting. Analyses of the sedimentology and structure of these deposits helped determine their genesis and the nature of the late glacial environment. Recent road construction opened-up exposures through these landforms (Figure 3.1). When the sediments were not exposed their interpretation was based on drill logs (Figure 3.1).

3.3.2 Hummocks

The stratigraphy of several hummocks (see Table 3.1) was examined. Although all of these hummocks appeared to be morphologically similar, their deposits varied substantially. Three morphologically typical, yet sedimentologically and structurally different, hummocks were selected for discussion. The three hummocks are located along the east boundary of Elk Island National Park (Figure 3.1). The first two exposures are found within adjacent hummocks, separated by a depression. The third lies about 2.5 kilometres north and is situated at a higher elevation (Figure 3.2). A fourth hummock, located immediately south of Astotin Lake, (Figure 3.1) was investigated via a drill log. Here, a complete vertical sequence from surface to bedrock was obtained. These four hummocks are described in detail and their genesis interpreted.

Figure 3.1 The locations of morainic landform/till sediment sites examined within the study area



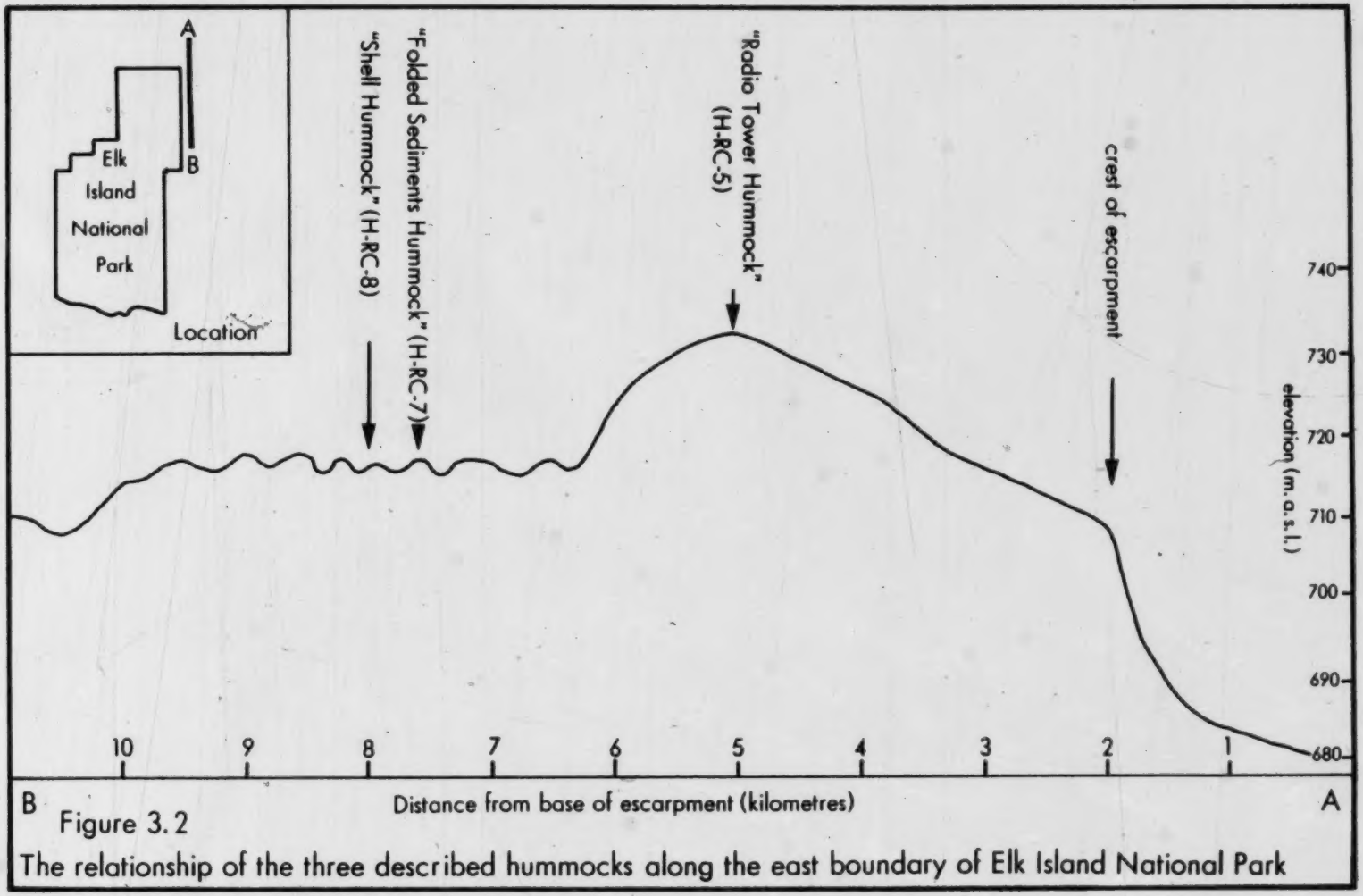


Figure 3.2

The relationship of the three described hummocks along the east boundary of Elk Island National Park

3.3.2.1 **Shell Hummock (H-RC-8)**

This hummock is so-named because shells were found dispersed within laminated sediments and diamicton. The exposure is aligned north-south and has an east-facing aspect. The section is 112 metres long with a height of 2.8 metres along the central part (Figure 3.3). The section height was artificially created by road construction. To the north and south long slopes lead into deep depressions. The section no longer exists.

Observations and Interpretations of the Sediment Unit Characteristics:

Three major units are exposed within the section (Figure 3.3). Two diamicton units comprise the majority of the section. However, a unit of finely laminated silt and clay also occurs and is most important for the interpretation of landform genesis.

Unit B; Laminated silt and clay:

The internal character of this section is "highlighted" by a more-or-less continuous band of parallel-laminated silt and clay (Figure 3.4). The band has a variable thickness, averaging 40 centimetres (Figure 3.3). The occurrence of laminated, fine-grained, sediments enclosed in diamicton, and situated within the central zone of hummocks, is common in the area. Similar sediments are found within hummocks H-RC-6,9,10,11 and 12 (Figure 3.1).

The sub-horizontal band, although intact through its central part, splays at both ends. On either side of the hinge points individual beds are persistent and easily traced (Figure 3.3b). Deformations, restricted to some beds, are also noted within the band (Figure 3.3a).

This unit contained an array of freshwater flora and fauna. The palaeoenvironment was obviously suitable for their colonization. A sample of freshwater shells was removed from this unit (Figure 3.3). Two gastropod species (*Gyraulus parvus [Say]* and *Lynmaea stagnalis*) and a bivalve species (*Pisidium sp.*) were identified by the author. All three species are known to inhabit cool-water environments and have been previously identified in superglacial pond sediments within the Cooking Lake moraine (Emerson, 1983). Part of

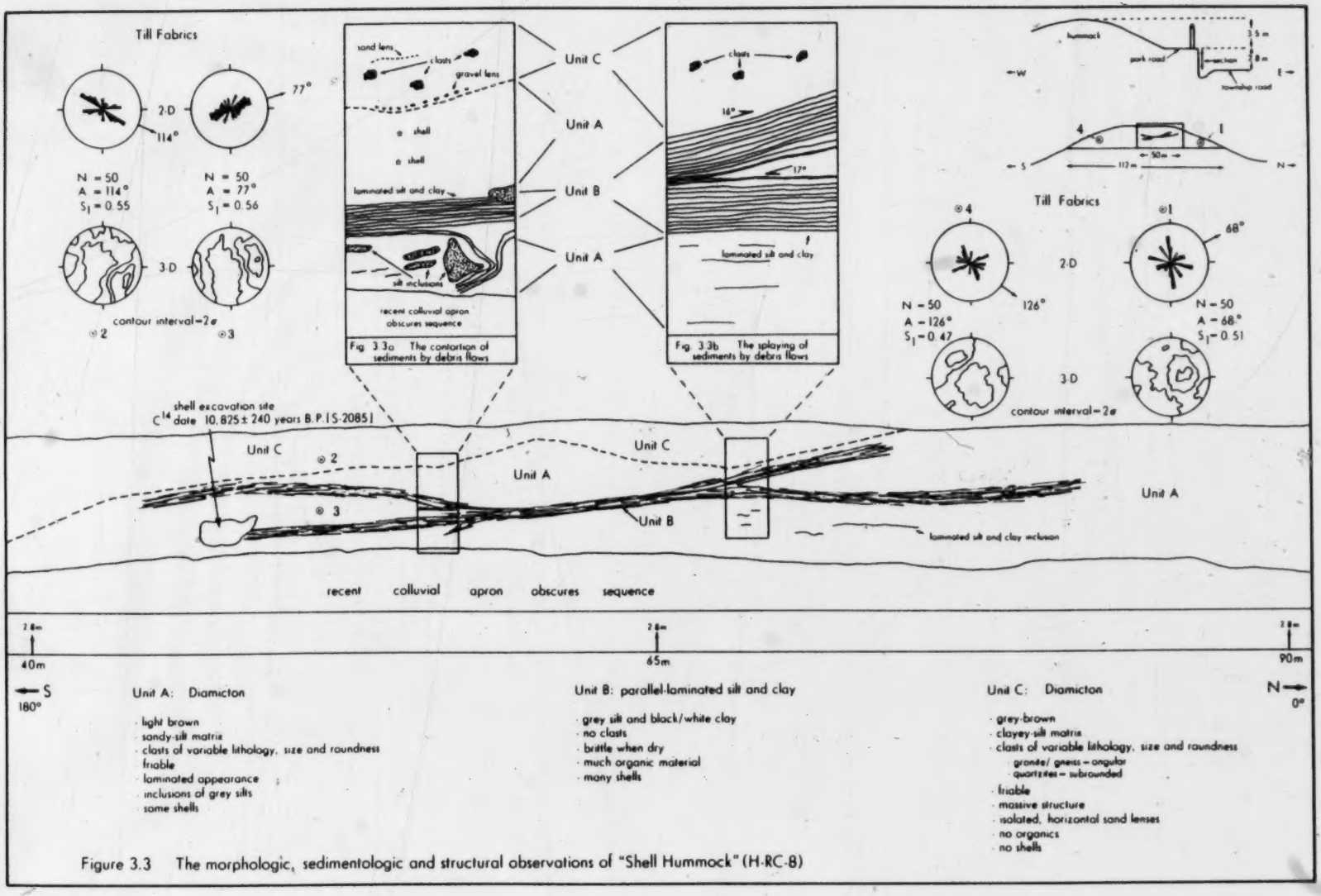


Figure 3.3 The morphologic, sedimentologic and structural observations of "Shell Hummock" (H-RC-8)

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Figure 3.4 The internal character of the central part of "Shell Hummock" (H-RC-8)

this shell sample was sent to the Saskatchewan Research Council for radiocarbon dating. A date of 10,825 + 240 years BP [S-2085] was obtained.

The unit of laminated silt and clay is interpreted as pond sediments which accumulated in a superglacial depression. Freshwater fauna and flora flourished. Normal fine-grained sedimentation was disrupted in several instances by pulses of debris introduced into the pond, probably by mass movement. These penecontemporaneous deformations are expressed two ways; first, by the contortion, incorporation and mixing of the laminated sediments into the debris flow (Figure 3.3a), and secondly, by the temporary interruption of pond sedimentation without deforming the underlying sediments (Figure 3.3b).

Units A and C; Diamicton:

The contact between the two diamicton units is unclear. Both units are matrix-dominated with widely dispersed pebbles and small cobbles. Within each unit granite/gneiss clasts are angular while the quartzites are subrounded; striations and pits are absent. Both units have a low degree of consolidation.

However, closer inspection reveals subtle differences between the two diamictons. The colour (light brown) and the texture (sandy-silt) of unit A's matrix differ from those of unit C (grey-brown; clay-silt). Unit A has a faint laminated structure with many inclusions of grey, massive silts and finely laminated clays. In contrast, unit C is massive with only rare occurrences of horizontal sand stringers. In addition, complete shells are found scattered throughout unit A.

Four samples of pebble fabrics were measured within the diamictons (Figure 3.3). The fabric results indicate a wide variability of between-site and within-site preferred orientations. The strengths of the preferred orientations for samples 1, 2 and 3 (Figure 3.3) are relatively weak (S1=0.51, 0.55 and 0.56 respectively) whereas sample 4 has an extremely weak orientation (S1=0.47). These results are not inconsistent with the interpreted mechanism of debris flows which probably entered the depression from many directions. The degree of saturation for each flow was presumably different, overlapping

and mixing relationships during resedimentation being anticipated. Some post-depositional readjustment would also be expected.

The diamicton units are both interpreted as sediment flow diamicton. The presence of deformed inclusions of pond sediments, and complete shells within unit A, indicate that debris entering the pond reworked the pre-existing sediments. Unit A is therefore assumed to be a subaqueous sediment flow diamicton. Unit C is interpreted as a subaerial sediment flow diamicton which entered the depression during the later stages of the hummock formation.

Hummock Genesis:

A relief inversion, let-down hypothesis is applied to the formation of this hummock. Several stages of development are depicted in Figure 3.5.

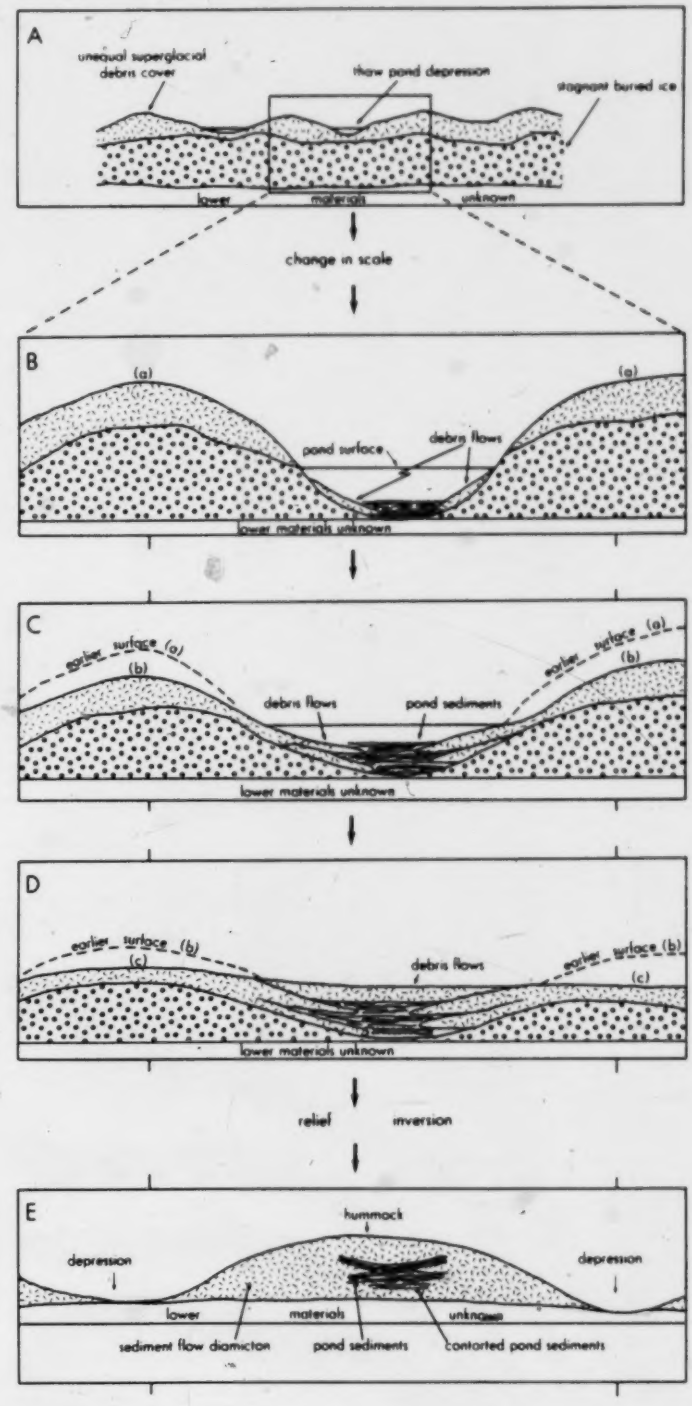
Phase 1: The initial phase in the hummock formation is represented by thaw pond depressions on the stagnant glacier surface. This unstable phase was preceded by a period of more stable conditions when the debris cover was continuous, protecting the ice core from top melting. Once the thaw ponds formed the uneven surface topography was accentuated and superglacial mass movement commenced.

Phase 2: In phase 2 mass movement into the pond contorted and encorporated the pre-existing pond sediments. The debris flows during this stage originated from a high elevation and flowed *en masse* in a confined situation. Due to the velocity and confined nature the debris flows were capable of distorting the pond sediments. Following these debris flows normal pond sedimentation continued.

Phase 3: Figure 3.5c illustrates that the pond became enlarged and the relief difference between the pond and the ice/sediment surface decreased. A second stage of mass movement ensued. During this time, reduced slope angles and longer travel distances caused the viscous mass to only temporarily disrupt pond sedimentation without disturbing the pre-existing sediments. Normal pond sedimentation followed.

Phase 4: Debris flows had now infilled the pond. The surface topography was almost level with large blocks of ice remaining at the perimeter.

Phase 5: With relief inversion the pond sediments and flow deposits, which originally filled



Phase 1, Start:

Thaw pond depressions form on the surface of the stagnant ice. This accentuates the uneven surface topography and promotes mass movement into the pond.

Phase 2:

Mass movement into the pond contorts and encorporates the pre-existing pond sediments.

Phase 3:

The pond has enlarged and a second stage of mass movement only temporarily disrupts the pond sedimentation.

Phase 4:

Debris flows have infilled the pond. Large blocks of buried ice remain around the perimeter of the pond.

Phase 5, Final Configuration:

The relief has been inverted, leaving the pond and diamicton flow sediments upstanding. The buried ice at the perimeter has melted leaving depressions.

Figure 3.5 The interpreted let-down genesis of "Shell Hummock" (H-RC-8)

the depressions, became upstanding. Final melting of the ice cores left the intervening depressions.

3.3.2.2 **Folded Sediments Hummock (H-RC-7)**

This section is aligned north-south and has an east-facing aspect. It is 108 metres long with a relatively constant height of 1.8 metres along the central segment. This section was also artificially created by road construction (Figure 3.6). To the north and south the hummock slopes grade steeply into deep depressions. This section no longer exists.

Observations and Interpretations of the Sediment Unit Characteristics:

Three major units occur within the section (Figure 3.6). The most prominent is a large folded unit of bedded gravel, sand, silt and clay (Figure 3.7). This unit is surrounded by a relatively thin, yet continuous, unit of silty-clay diamicton (Unit B). A diamicton (Unit C) with sorted and stratified sediment inclusions comprises the remainder of the hummock section.

Unit A; Folded gravel, sand, silt and clay:

A detailed sketch of this unit is given in Figure 3.6a. The sedimentary sequence generally shows fining upward but a gravel bed caps the sequence. This block of unlithified sediments has been both folded and faulted. Individual beds can be traced around the fold, although they are interrupted by a major fault which dips at an angle of 59° to the south. The throw of the normal fault is 30 centimetres. Numerous small faults are apparent within individual beds. Of particular interest is the contrast in clast lithologies between this unit and the enclosing diamicton. A visual appraisal of the gravel lithologies within this block revealed a dominance of quartzites (approximately 80:20 quartzite:crystalline ratio). The enclosing diamicton has predominantly crystalline clasts.

The block is interpreted as fluvial/glaciofluvial sediments which had been previously quarried and incorporated into the glacier ice, most probably in a frozen state. The block was subsequently folded during transport. The faulting probably occurred post-depositionally as the debris-rich ice melted out around it.

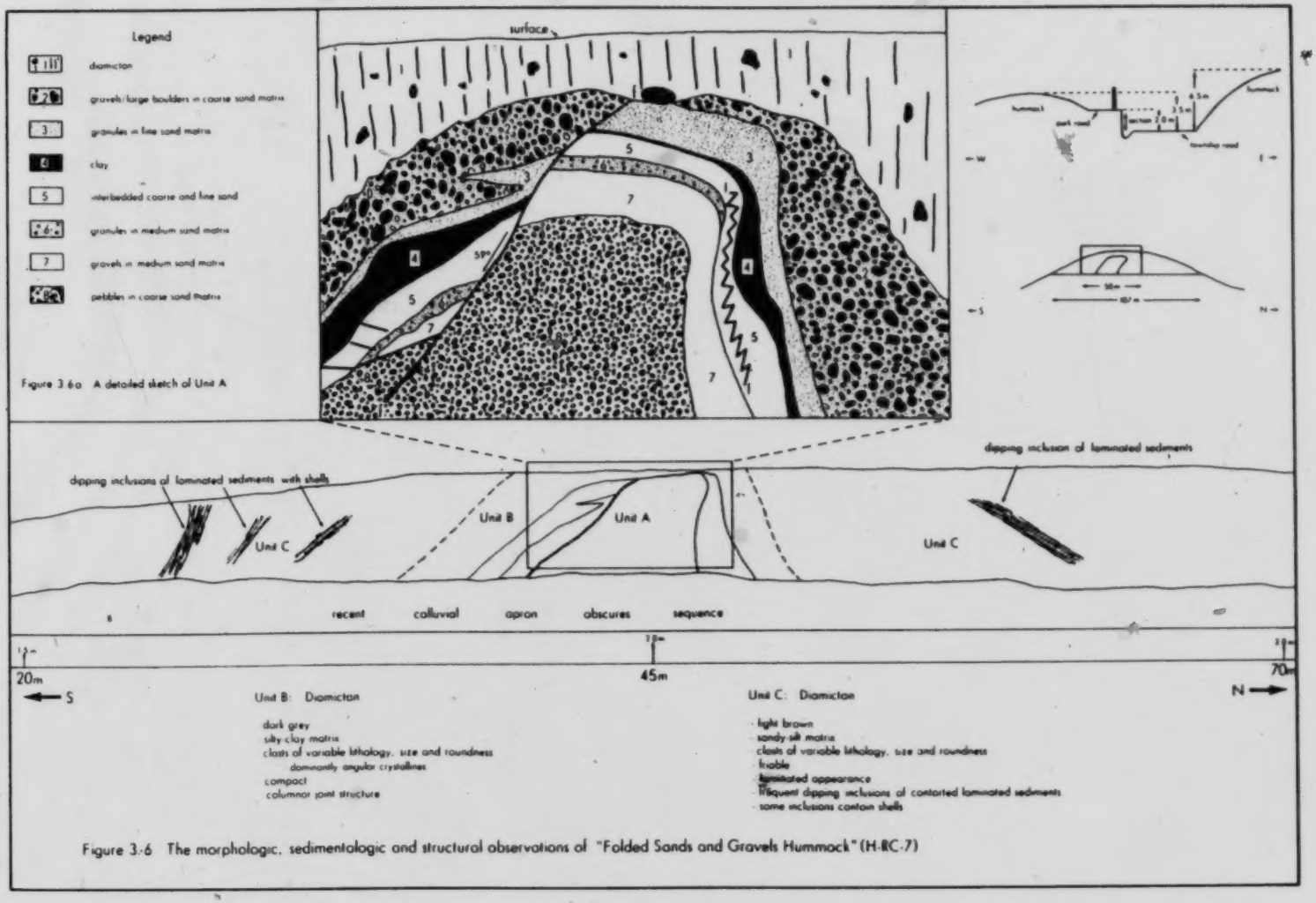


Figure 3.6a A detailed sketch of Unit A

Figure 3.6 The morphologic, sedimentologic and structural observations of "Folded Sands and Gravels Hummock" (H-BC-7)

Unit B; Diamicton:

This silty-clay diamicton unit encloses the block of sorted sediments. The contact between units A and B is wavy (Figure 3.6a). The clasts are very angular and predominantly granites and gneisses. A vertical joint structure is apparent in this diamicton. This unit is interpreted as melt-out till, deposited from the debris-rich ice which transported the unlithified block.

Unit C; Diamicton:

Unit C represents the major part of the hummock. This silty-clay diamicton contains frequent, dipping and contorted inclusions of laminated sediments. These inclusions vary in texture, most being fine-grained and containing white fibrous material and shells. The dip of some inclusions conforms to the dip of units A and B. In the north part of the hummock the inclusions generally dip north and in the south they generally dip south. High angle dips were recorded to the south (almost vertical) (Figure 3.8) and lower angle dips (25°-35°) to the north.

The inclusions of laminated sediments are interpreted as displaced fragments of pond sediments. The diamicton is interpreted as a sediment flow diamicton, at times subaqueous, and at other times subaerial, dependent upon the presence/absence of incorporated pond sediments. It was impossible to differentiate subaerial and subaqueous units and/or phases of superglacial mass movement.

Hummock Genesis:

The genesis of this hummock was interpreted from stratigraphic, sedimentologic and structural evidence. In this hummock both lower ice deposits (units A and B) and superglacial deposits (unit C) are proposed.

The block of stratified sediments (unit A), which contains both Rocky Mountain-derived and Canadian Shield-derived gravels, is definitely not an incorporated block of preglacial Saskatchewan Gravels and Sands (Stalker, 1968). On the other hand, as the surrounding till contains more abundant Shield clasts and the sorted gravels are

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Figure 3.7 The folded sediments (Unit A) in the central part of hummock H-RC-7

Figure 3.8
A vertically dipping lacustrine sediments inclusion in the southern flank of hummock H-RC-7

dominated by quartzites, the latter sediments are unlikely to be *in situ* stratified deposits which accumulated in a subglacial tunnel. Further, the sedimentary sequence (with gravels resting on fine-grained sediments) is characteristic of unconfined alluvial deposition not found in confined subglacial tunnels. Consequently, it is suggested that the sediments are of fluvial or glaciofluvial origin, a block of which was incorporated by over-riding ice. The source-area of this block was probably to the northeast. The sediments may have been deposited prior to the last glacier advance by an east flowing river, possibly the ancestral North Saskatchewan. This river must have flowed from the Rocky Mountain area, and through previously deposited Laurentide glacigenic sediments, to produce the lithologic *mix* characteristic of the block sediments. The block may have been folded in glacier transport with good preservation of the primary internal sedimentary structure. Further folding may have been accomplished as the block was eventually deposited. Faulting within the block occurred as the enclosing debris-rich ice melted out. The debris-rich ice, once all the interstial ice had melted, became the melt-out till of unit B.

Differential ablation in the upper ice allowed shallow depressions to form, in which ponds developed and molluscs thrived. Following this stage two possibilities exist for hummock formation. The first is similar to that interpreted for hummock H-RC-8 (see Figure 3.5). However, in this case the superglacial pond sediments were much more disturbed by mass movement and thus are found only as fragmented inclusions within the diamicton. With differential let-down and relief inversion these inclusions were left dipping in nearly vertical and symmetrical configurations. The second possibility is that this hummock represents an aborted pingo. As the superglacial ponds drained permafrost may have aggraded into their sediments. The sands and gravels of unit A would have been an ideal aquifer where segregated ice could develop. The growth of the pingo may have terminated with a change in drainage locally, therefore reducing the water supply to the growing ice core. Hence injection rather than draping (with differential melt-out) may explain the folding of the sand and gravel unit, as well as the symmetrical dips of the pond sediment inclusions.

3.3.2.3 Radio Tower Hummock (H-RC-5)

This section is cut in a north-south orientation and has a west-facing aspect. Sixty metres long, with a maximum height of 4.3 metres, it has a symmetrical hummocky appearance. Unlike the previously described hummocks it is more isolated and is not flanked by deep depressions.

Observations and Interpretations of the Sediment Unit Characteristics:

Three major units are differentiated on the basis of colour, clast frequency, degree of compaction and, particularly, structure. The contacts between these units are most easily recognized in the southern end of the section. A fourth, very thin unit drapes the entire hummock (Figure 3.9).

Unit A; Diamicton:

This lowermost diamicton has a yellow-brown, silty-clay matrix with infrequent angular clasts ranging in size from small pebbles to large boulders. Characteristic of this unit is the frequent occurrence of small lenses of stratified sediments (Figure 3.9a). The structure of this highly indurated diamicton is blocky.

The diamicton is interpreted as till; its formation attributed to subglacial melt-out processes. Deposition by lodgement is precluded as the formation and preservation of the primary structure, with associated stratified lenses, is incompatible with layer by layer accretion or *plastering on* processes. The sub-horizontal lenses of sorted sediments were probably formed synchronously with melt-out within the isothermal basal layers of the ice. Slow basal melt-out, with geothermal heat causing melting, occurs when the superglacial debris cover, once equal to the thickness of the active layer, inhibits ablation in the upper parts of the buried ice. Small cavities are expected to develop within the melting ice layers. Laminated sediment lenses would result from deposition of sorted materials within these cavities (Shaw, 1979). Only small lenses of sorted material are expected as the bulk of the water is excavated instantaneously (Boulton, 1970b).

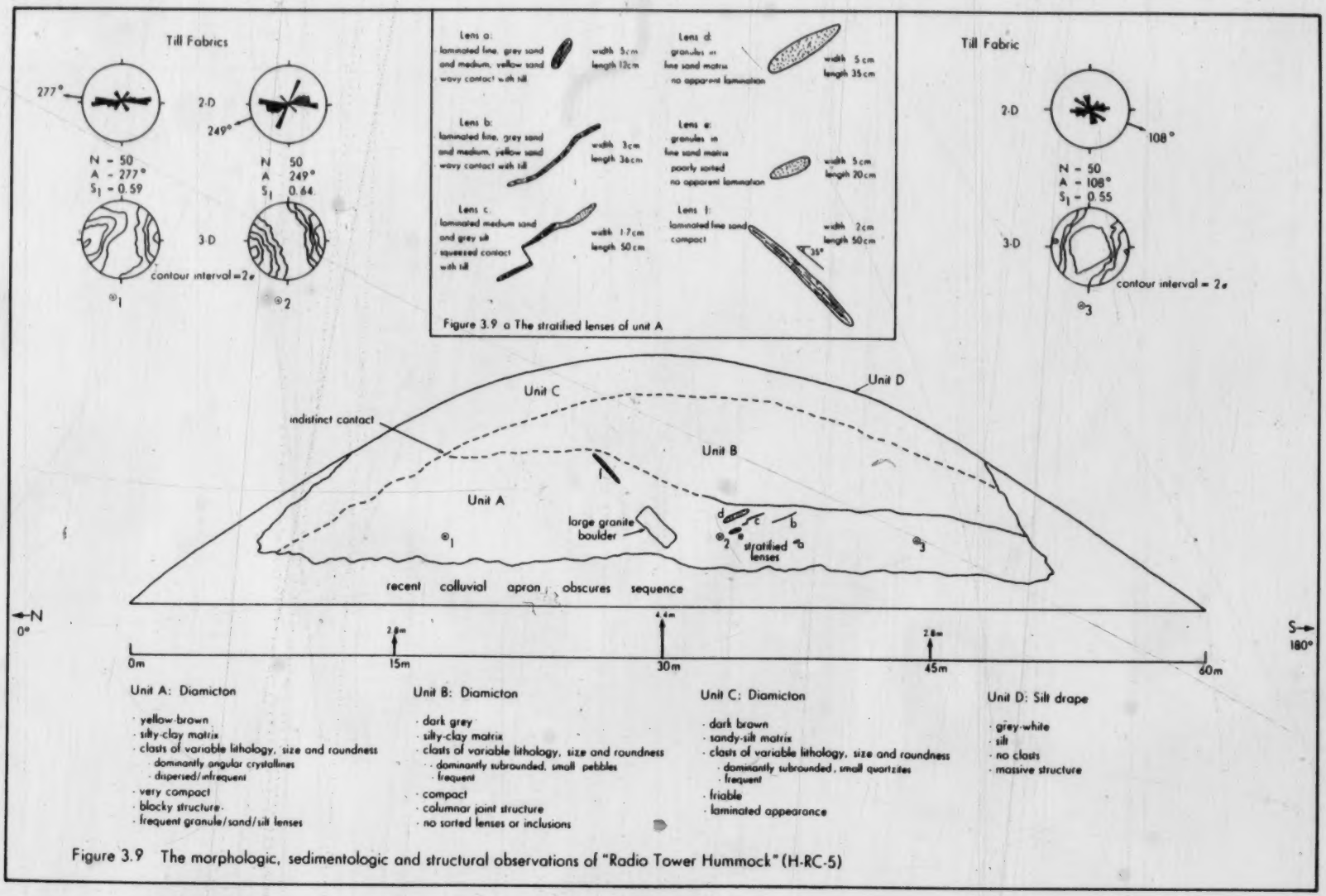

Figure 3.9 a The stratified lenses of unit A

Figure 3.9 The morphologic, sedimentologic and structural observations of "Radio Tower Hummock" (H-RC-5)

Preservation of the englacial structure (with disturbance due only to readjustment as the interstitial ice melts out) is predicted. Although till fabrics A1 and A2 have relatively high strengths of preferred orientation (S1=0.59 and 0.64 respectively), the orientation of the principal eigenvector in both cases is at variance with the assumed ice flow direction. These two fabrics, as well as fabric A3, showing a high dispersion of clast orientations, may indicate a zone of reworking associated with subsidence and/or sliding of the overlying sediments (Shaw, 1982). Englacial material which is let down onto still underconsolidated diamicton will also cause differential loading. The preferred dip of the lenses toward the central portion of the hummock is evidence of this loading and differential subsidence. Further, lens C is drag-faulted. Fabric A3, a girdle fabric, is closer to the zone of possible sliding of the overlying unit B deposits and thus shows an even lower S1 value.

Unit B; Diamicton:

Unit B has a dark grey, moderately compact silty-clay matrix. Pebble-sized, subrounded clasts of mixed lithologies are frequent. The unit has good columnar jointing, joint spacing being approximately 1 centimetre. The joints are curvilinear and isoclinal (Figure 3.10).

The interpretation of unit B is more problematical as direct evidence for formation by melt-out or superglacial flow is lacking. The good columnar structure indicates a high clay content and/or deposition and dewatering in the absence of great vertical pressure. Unit B may be interpreted as *ablation melt-out* till, with a heat source from the ice surface. It may have been lowered onto the basal melt-out till of unit A. Alternatively, this unit could be interpreted as a *parautochtonous* flow till, described by Boulton (1976) as a subdivision of flow till which has never been exposed subaerially and thus remains massive.

Unit C; Diamicton:

Unit C has a dark brown, silty-clay matrix, the degree of compaction being very low. Coarse clasts are highly dispersed and infrequent. The structure has a distinctive

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Figure 3.10

The contact between unit A and unit B in the southern flank of hummock H-RC-5

(Note the structural differences between the two units)

laminated appearance. This unit is interpreted as a subaerial sediment flow diamicton, analogous to Boulton's (1976) *allochtonous* subdivision of flow till. The lamination is inherited from the mass movement processes in the superglacial environment and is not related to the glacier ice source.

Unit D; Silt drape:

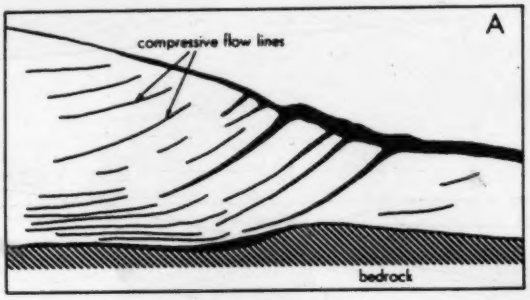
A very thin veneer (30 centimetres) of massive, well sorted, grey-white silt drapes the entire landform. This unit is interpreted as an aeolian deposit, laid down after the deposition of the glacigenic sediments.

Hummock Genesis:

The hummock sits on top of a bedrock *high* and is located about two kilometres southwest of the northwest-southeast trending escarpment (Figure 1.4). Ice flow direction is assumed to have been from the northeast. As the ice sheet encountered this obstruction in the bed it locally developed compressive flows. The upward component of flow during compression transported much debris from the englacial position to the glacier surface (Figure 3.11; Phase 1).

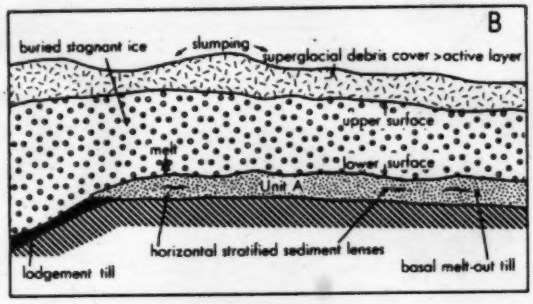
With climatic amelioration during deglaciation this area acquired a hummocky surface due to differential ablation and/or increased concentrations of material where outcropping debris bands reached the surface (Figure 3.11; Phase 2). Ablation of the upper surface of the buried stagnant ice was inhibited by the thick superglacial debris cover. Geothermal heat provided the only heat source for slow undermelt and the formation of the basal melt-out till and associated sorted lenses (unit A).

With continued basal melting the hummocky surface configuration was accentuated. Slumping and sliding of the superglacial debris exposed the upper surface of the buried ice. The surface heat source allowed the ablation melt-out till, or parautochtonous flow till (unit B), to form. As ablation continued and unit B thickened the material was lowered or slumped onto the still underconsolidated basal melt-out till, thus distorting the previously formed, horizontal, stratified lenses and primary englacial



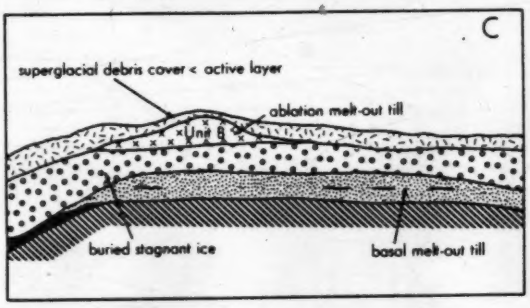
Phase 1, Start

As the southwest flowing ice sheet encountered the bedrock escarpment it locally developed compressive flow. The upward component of flow delivered much debris to the glacier surface.



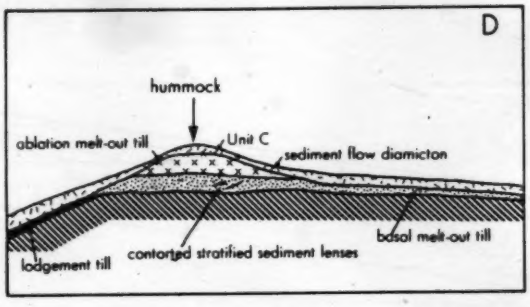
Phase 2 (with change of scale)

During deglaciation the area acquired a hummocky surface with a variable thickness of superglacial debris. Geothermal heat provided the only heat source for slow undermelt and the formation of basal melt-out till with associated sorted sediment lenses (Unit A).



Phase 3

With continued undermelt the hummocky surface was accentuated. Slumping and sliding of the superglacial debris exposed the upper surface of the buried ice allowing ablation melt-out till (Unit B) to form.



Phase 4, Final Configuration

The superglacial environment continued to be active and debris flowed in all directions. With final melting of the buried ice a hummock developed, covered and flanked by sediment flow diamicton (Unit C).

Figure 3.11 The interpreted let-down genesis of "Radio Tower Hummock" (H-RC-5)

structure.

The superglacial environment continued to be active. The upper diamicton (unit C), subjected to subaerial processes, acquired a crude stratification as it flowed in numerous directions. After melting of the last remnant bodies of buried ice the landscape included the upstanding hummock, flanked by lower undulating areas dominated by superglacial flow till deposits (see Figure 3.2). After the hummock was created strong winds from the north–northwest deposited a thin veneer of aeolian sediments.

3.3.2.4 **Astotin Lake Hummock (H-BR-45)**

This hummock is located approximately 200 metres south of, and 8 metres above, Astotin Lake (Figures 3.1 and 3.12). Many morphologically similar hummocks are found in this zone of the research area. As no exposures in these hummocks were found a large drilling rig was contracted to bore a single hole.

Observations and Interpretations of the Sediment Unit Characteristics:

The generalized stratigraphy, interpreted from the borehole record is given in Figure 3.13. Five units were differentiated on the basis of colour, texture, degree of consolidation, moisture content, presence/absence of organic materials and structural attributes. The contacts were poorly defined. Two radiocarbon dates were obtained from small twigs and grasses extracted from the 11.5 and 14.5 metre levels of the borehole.

Unit C; Laminated silt and clay:

Unit C is approximately 5 metres thick and is comprised of finely laminated silt and clay with an abundance of organic materials. No coarse clasts were found in these black, friable sediments. The sediments are interpreted as having accumulated in a pond/lake environment.

Units A, B, D and E; Diamicton:

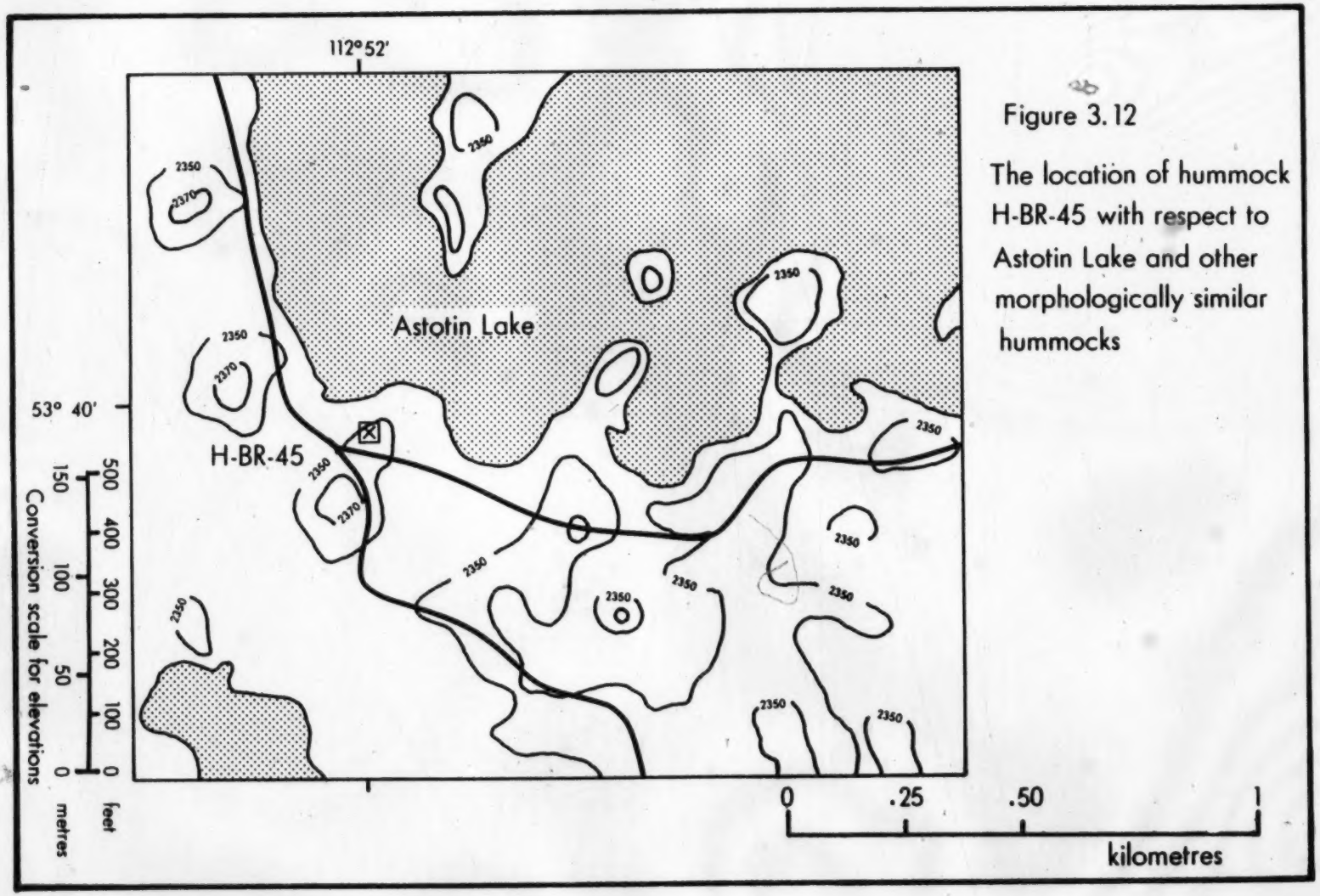


Figure 3.12

The location of hummock H-BR-45 with respect to Astotin Lake and other morphologically similar hummocks

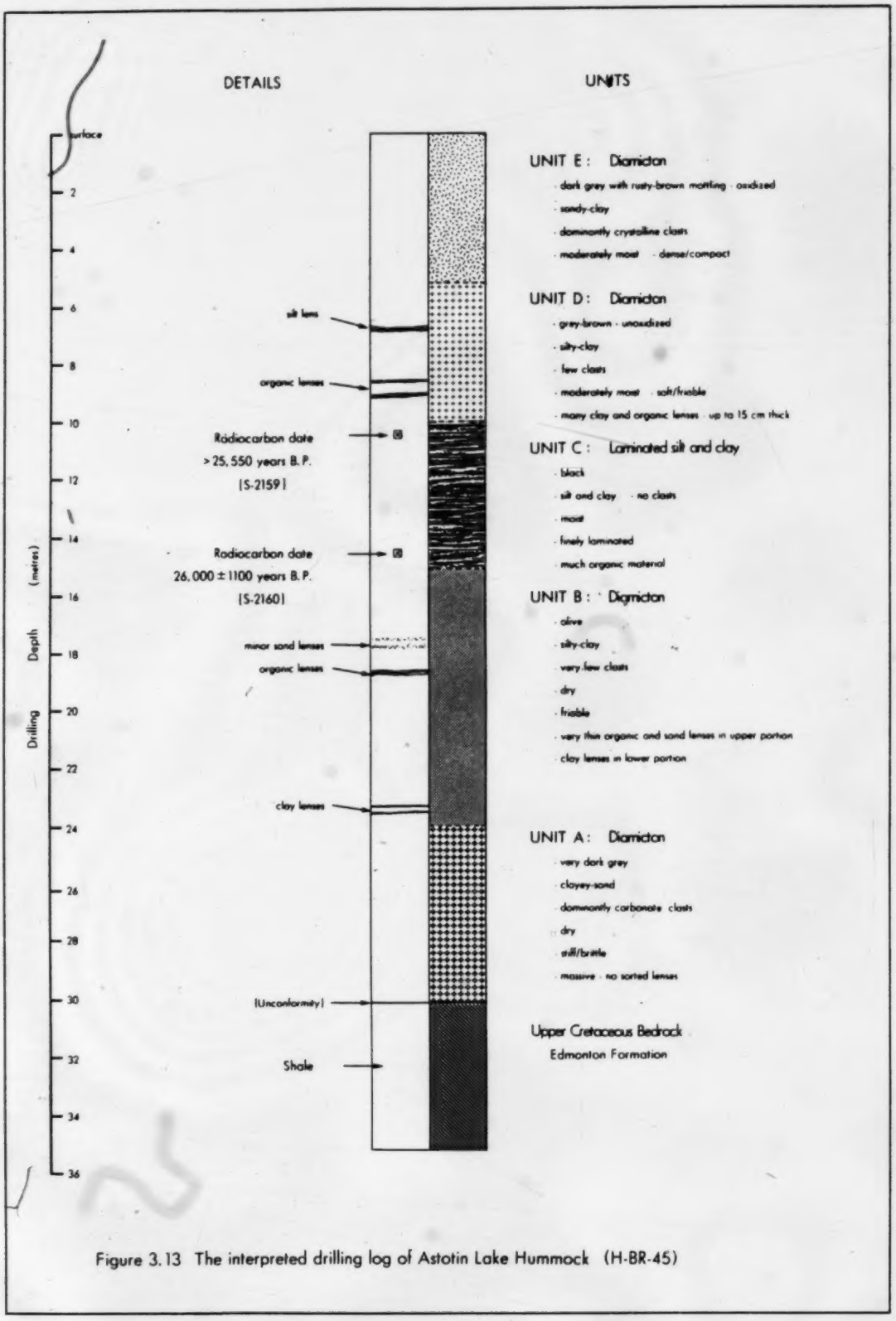


Figure 3.13 The interpreted drilling log of Astotin Lake Hummock (H-BR-45)

Four diamicton units were tentatively identified (Figure 3.13). Without detailed structure observations it is difficult to determine whether these diamicton units are indeed till. Only unit A is interpreted as till. Additionally, unit D may also be a till although the occurrence of much stratified and organic material renders this questionable. However, as ice advanced and overrode the pond/lake sediments of unit C it probably eroded and incorporated these sediments, later depositing them through melt-out. Units B and E are most probably sediment flow diamictons. The occurrence of organic lenses in unit B indicates probable subaerial reworking and deposition of these deposits. The mottled appearance and textural attributes of unit E are analogous to the sediment flow diamictons observed and described in hummocks H-RC-7 and H-RC-8.

Interpretation of the Stratigraphic Sequence:

At least two episodes of glacial activity, separated by nonglacial conditions, are suggested by this sediment sequence. This interpretation is based on the two radiocarbon dates from unit C (25,550 yrs. B.P. [S-2159] and 26,000 +1,100 yrs. B.P. [S-2160]) (see Appendix 2). Several authors (e.g. Reeves, 1973; Stalker, 1977; Clayton and Moran, 1982) have reconstructed the chronology of Wisconsinan glacial fluctuations through radiometric dating. Generally a long nonglacial interval is presumed from about 55,000 yrs. B.P. to between 30,000 and 20,000 yrs. B.P. for the western interior of North America. Therefore, it is quite possible that the sediments of unit C were deposited within this nonglacial interval. However, caution is clearly required in treating dates in this range as finite measurements.

Stratigraphically below and above unit C the combined units A/B and D/E respectively may represent single episodes of glacial activity. The lower unit of each pair may represent subglacial/englacial deposition whereas the upper units may reflect superglacial deposition.

3.3.3 Prairie Mounds

Prairie mounds (see Table 3.1) are very common landforms within the study area and are often found in close association with hummocks. These prairie mounds usually stand alone, but in some cases they share rims (Figure 3.14). As no exposures were found in prairie mound rims a solitary prairie mound was selected for study from aerial photograph interpretation (Figure 3.15).

3.3.3.1 Beaver Pond Exhibit Prairie Mound (PM-MR-48)

This prairie mound is located northeast of Astotin Lake (Figure 3.1) and is more accessible than most because it is adjacent to the main road through the park. Morphometric analysis, using a composite of interrelated Abney level slope profiles, was employed to determine the size and form of the prairie mound (Figure 3.16). This type of survey (Young, 1974) is rapid and is possible to carry out through fairly dense vegetation (Gardiner and Dackombe, 1977). Contours were drawn from calculated spot heights (Figure 3.17). Characteristic of this, and all prairie mounds, is the presence of a central depression enclosed by a nearly circular, raised rim (Figure 3.17). The basal diameter of the mound is approximately 100 metres and, with the exception of two places where the rim is breached, its height is approximately 3 to 4 metres above the central depression. The floor of the central depression is flat and at a slightly higher elevation than the intermound depressions (Figure 3.17).

Observations and Interpretations of the Sediment Unit Characteristics:

Test holes were drilled into the rim of the mound and the floor of the central depression using a *Minuteman* rig. The stratigraphy, interpreted from the drilling logs at four sites (Figure 3.17), is depicted in Figure 3.18. Drilling into the rim was extremely difficult due to the compact nature of the material. The small rig was capable of only a 2 metre penetration. However, this was sufficient to reveal that the rim was composed of a silty-clay diamicton. In the central depression a 4 metre graded sequence of laminated sand, silt and clay rested on top of a diamicton (Figure 3.18).

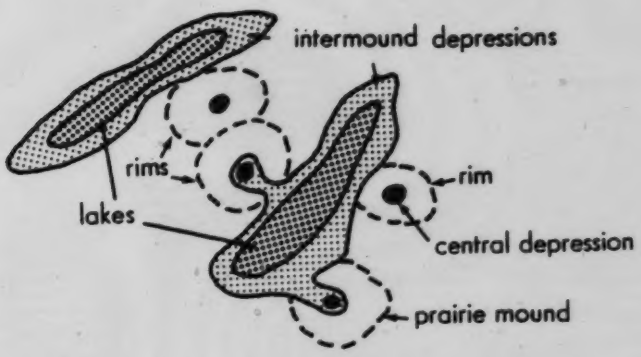


Figure 3.14 The prairie mounds of the study area often share rims

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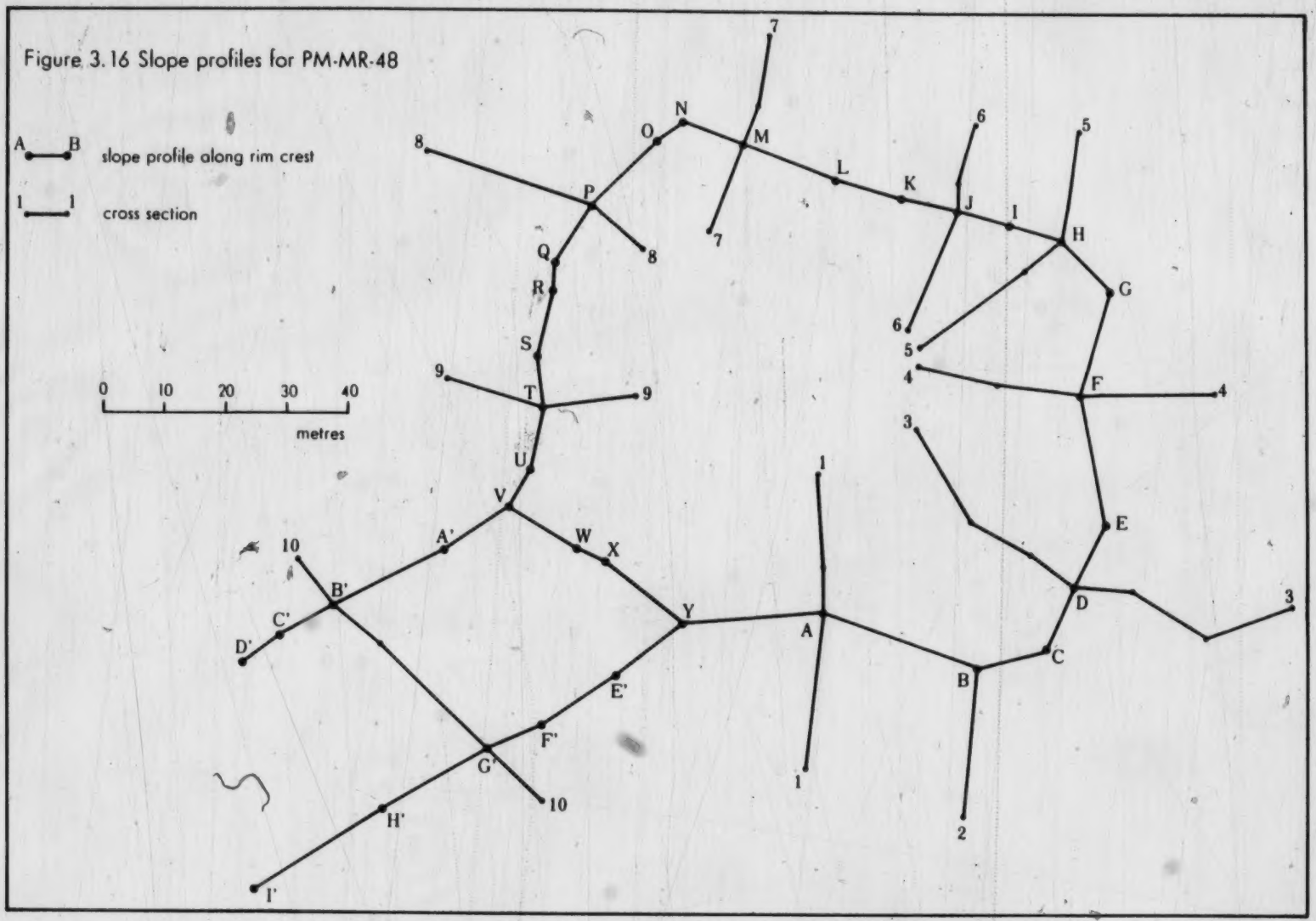
Figure 3.15 The relationship of prairie mound PM-MR-48 to other prairie mounds and intermound depressions

Figure 3.16 Slope profiles for PM-MR-48



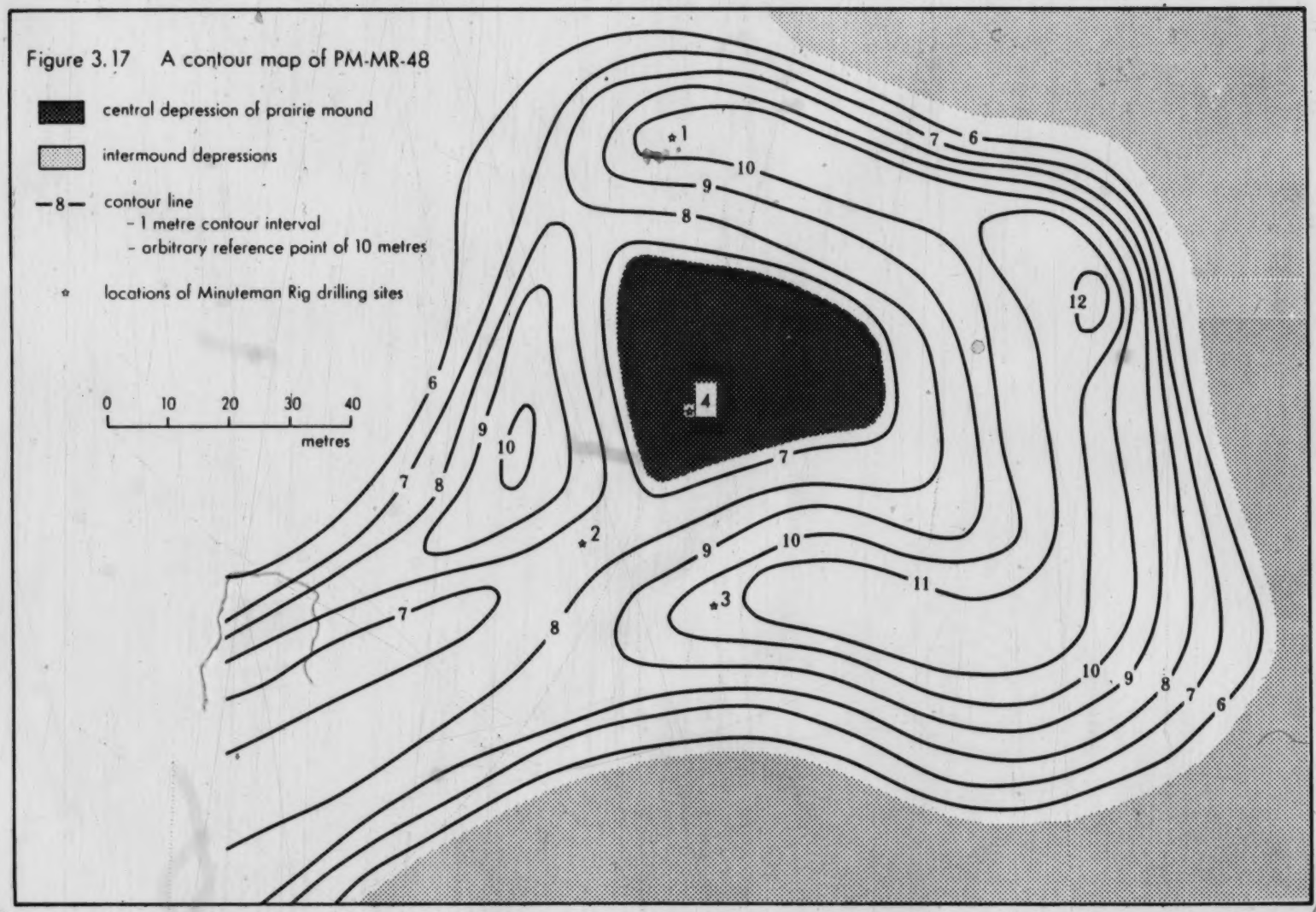


Figure 3.17 A contour map of PM-MR-48

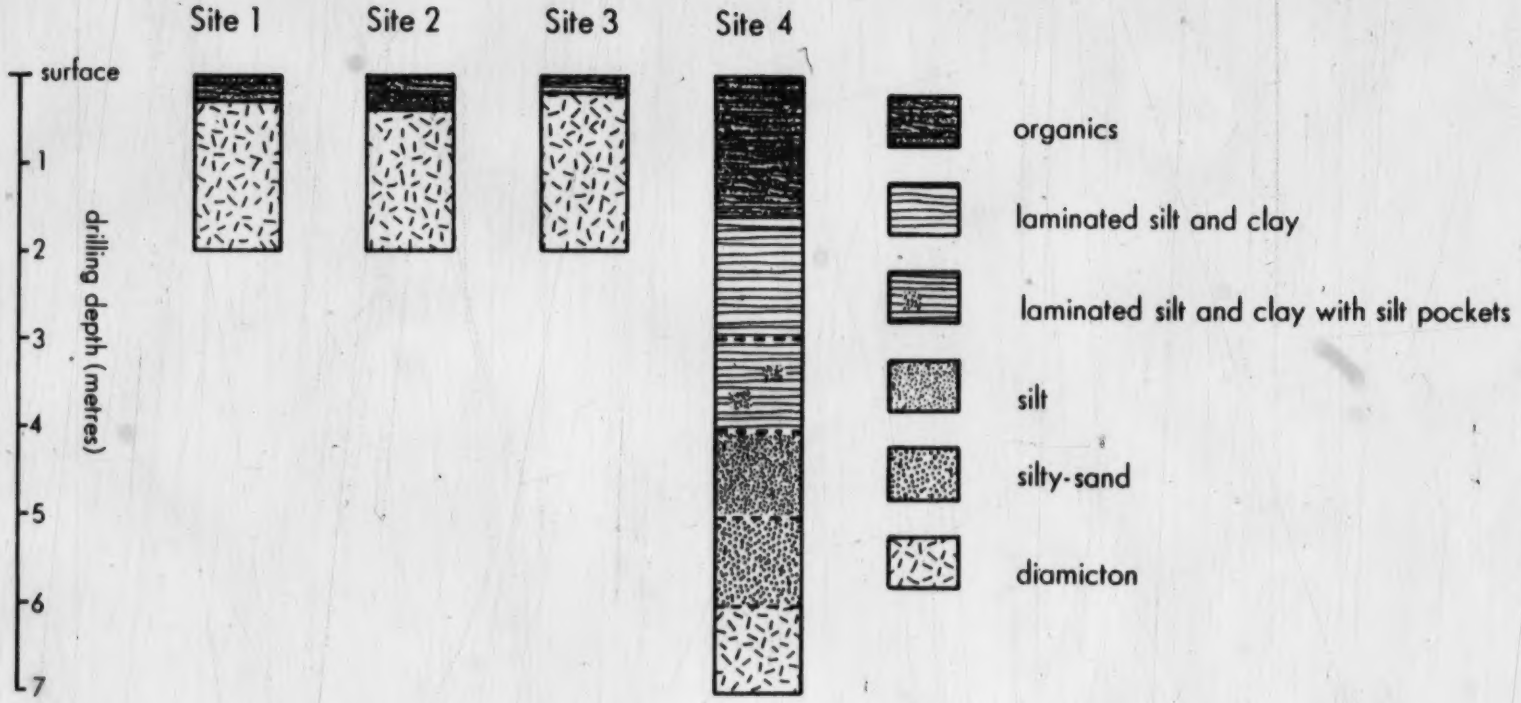


Figure 3.18 The interpreted drilling logs for PM-MR-48
(see Figure 3.17 for site locations)

Landform Genesis:

The formative phases of this prairie mound were interpreted using landform associations as well as the morphologic and sedimentologic information (Figure 3.19). Because this prairie mound is closely associated with hummocks, and the diamicton rims of other prairie mounds are sometimes shared, the landform genesis is interpreted to be essentially similar to that of the nearby hummocks. However, in contrast to the hummock genesis (see Figure 3.5) the final configuration of a prairie mound has a central depression. This central depression, and also the breached rims, may be explained by the decay of an irregularly shaped block of buried ice. Figure 3.19 depicts two cross-sections of the prairie mound and the influence of this buried ice irregularity.

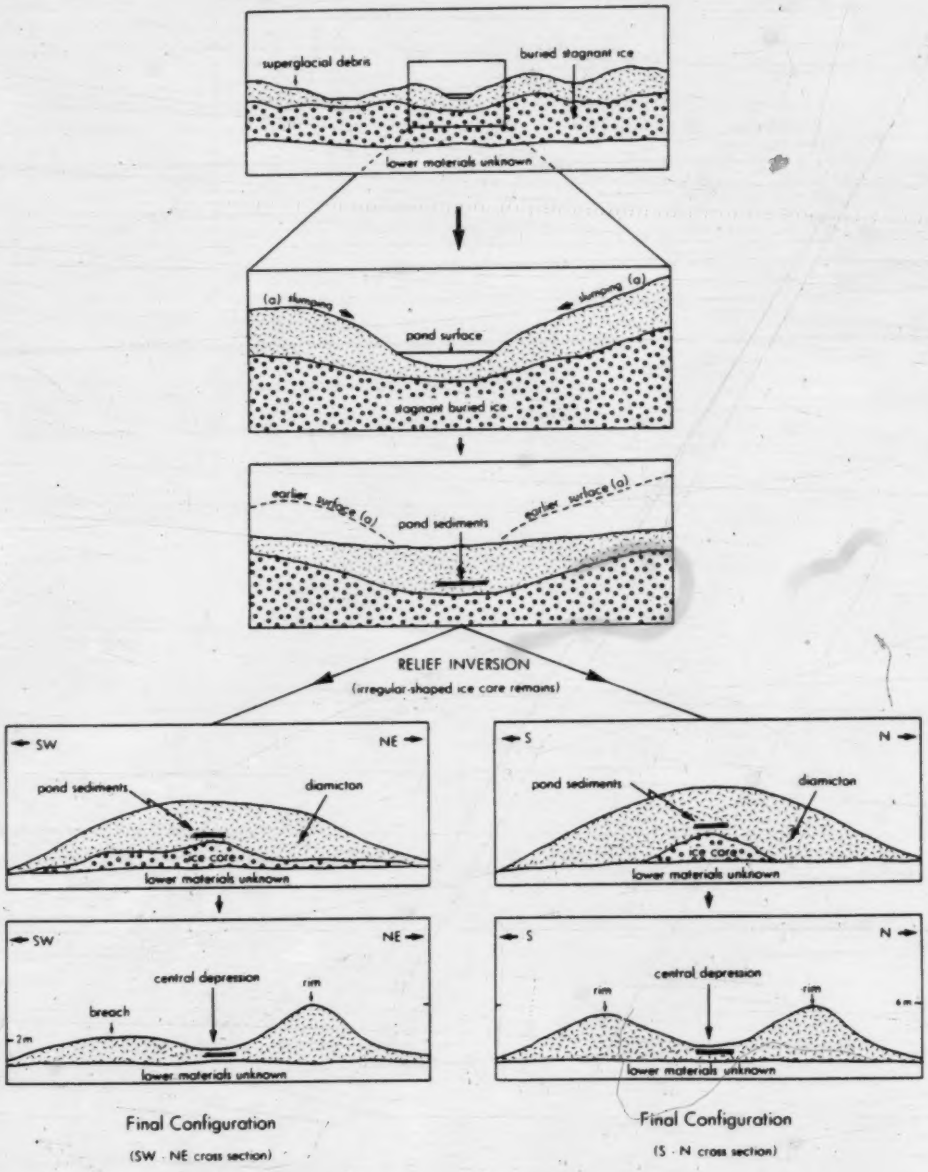


Figure 3.19 The interpreted genesis of PM-MR-48

4. GLACIOFLUVIAL/GLACIOLACUSTRINE LANDFORMS AND SEDIMENTS

4.1 Glaciofluvial Landforms and Sediments

4.1.1 Classification

Glaciofluvial landforms, like morainic landforms, have been classified in a variety of ways. Classifications have been based on three basic morphological expressions; ridges, hummocks and undulating surfaces. These classifications are solely descriptive because they only *list* a number of characteristic landform types and definitions (Lundquist, 1979). Consequently an overabundance of terms has resulted. However, Goldthwait's (1975) classification of glacial deposits (Table 4.1) and Sugden and John's (1976) classification of "Fluvioglacial ice-contact forms" (Table 4.2) are systematic. The latter classification is based on morphology and location with respect to the direction of ice movement. This is still inadequate because a morphogenetic approach should be the norm in all glacial geomorphologic classifications. Because morphology depends upon genesis it seems reasonable to include both for a meaningful, systematic classification.

Lundquist (1979) suggested a systematic classification of glaciofluvial landforms with a morphogenetic emphasis (Table 4.3). From stratigraphic evidence terms have been added to denote the position of deposition with respect to the glacier margin; inframarginal, marginal, extramarginal. Inframarginal deposits are further subdivided into subglacial, englacial and superglacial. Landforms are described and defined for each of the positions. Yet, without previous knowledge of the basic formation of such landforms as kames and eskers one can obtain little genetic information from the table alone. It does show, however, the differing positions in which each landform could have formed, thus implying polygenetic formation.

4.1.2 Eskers and Kames

Terminology for glaciofluvial landforms remains controversial, for example opinions differ regarding what is meant by the two major components; *eskers* and *kames*. The recognition that these landforms are polygenetic has helped alleviate some of the problems in definition. Price (1973) has partially clarified what it meant by each of these

DOMINANT MATERIALS		CONJECTURED SITUATION	SHAPE OR MORPHOLOGY
Lodgement till subglacial, basal, nonbedded, compact	Till till dominated, poorly sorted	Ground moraine under ice and off retreating edge	Till plain or rolling hills washboard moraine minor moraine
		Steamlined sliding melting base	Drumlin grooved till crag-tail
Ablation till superglacial, loose lens, bedded, contorted		End moraine at standing or advancing ice edge	Lobate/looped moraine push/thrust boulder belt lateral/interlobate moraine kame moraine
		Disintegration stagnant, decaying marginal area, buried ice masses	Controlled/uncontrolled disintegration dead ice knobs/rings disintegration ridge inverted lake
Glaciofluvial coarse cobble to silt, channeled or cross-bedded	Wash well sorted	Ice contact dipping, deformed, irregular beds in ice pit, channel, or tunnel	Esker crevasse filling chain (of kames)
			Kame field/kame and kettle kame moraine, moulin kame kame terrace/plain
Glaciolacustrine fines: fine sand to colloid clay, laminated		Proglacial at grade, uniform beds extending away from ice	Outwash plain/fan valley train kettled/pitted outwash collapsed outwash
			Lacustrine/marine delta, strand/raised beach glacial varve

Table 4.1 Classification of Glacial Deposits and Landforms (Goldthwait, 1975)

LINEAR FEATURES				NON-LINEAR FEATURES
Parallel to ice flow		Transverse to ice flow		(no consistent orientation)
Subglacial	Marginal	Subglacial	Marginal	
most types of eskers	some eskers kame terraces	subglacially engorged eskers some kames	crevasse fillings delta-moraines delta-kames	most kames collapse features kettles and pitted outwash

Table 4.2 A classification of glaciofluvial ice-contact forms (Sugden and John, 1976)

1. INFRAMARGINAL DEPOSITS	2. MARGINAL DEPOSITS	3. EXTRAMARGINAL DEPOSITS
1.1 Englacial supraaquatic	2.1 Supraaquatic	3.1 Supraaquatic
1.1.1 englacial eskers	2.1.1 marginal kames 2.1.2 lateral terraces	3.1.1 glaciofluvial fans 3.1.2 sandur plains 3.1.3 glaciofluvial river terraces 3.1.4 indifferent valley trains 3.1.5 residual deposits
1.2 Supraglacial subaerial supraaquatic	2.2 Water-level	
1.2.1 subaerial eskers 1.2.2 supraglacial kame deltas	2.2.1 marginal deltas	
1.3 Subaerial supraaquatic	2.3 Subaquatic	3.2 Water-level
1.3.1 eskers 1.3.2 kame fields	2.3.1 subaquatic (De Geer) eskers 2.3.2 subaquatic deltas	3.2.1 extramarginal deltas 3.2.2 proximal deltas
1.4 Subglacial supraaquatic	2.4 Supraaquatic-subaquatic	3.3 Subaquatic
1.4.1 engorged eskers 1.4.2 subcircular eskers	2.4.1 marginal eskers	3.3.1 gravel ridges
1.5 Subglacial supraaquatic-subaquatic		
1.5.1 eskers 1.5.2 transverse eskers 1.5.3 esker nets 1.5.4 subglacial kames 1.5.5 lee-side ridges 1.5.6 valley-side deposits		

Table 4.3 Suggested morphogenetic classification of glaciofluvial deposits (Lundquist, 1979)

terms. He stated (p. 139) that a kame consists of,

> " primary accumulations of sediments *in water* beneath, within or at the margin of an ice mass, that have a *mound* form resulting from the removal of supporting ice "

and that eskers are,

> " *ridges* of fluvioglacial deposits laid down by meltwater *streams* as *channel* deposits ".
>
> [italics by present author]

It can be seen that a kame has water involvement but not necessarily channelled flow. Thus kame deposits can be exceedingly variable and include glaciolacustrine deposits as well as slumped materials. Much emphasis is placed on ice-contact controls in their formation and the resultant mound form is a general morphologic rule.

In some instances *kame* is used as an adjective (e.g. kame delta, kame terrace) or as part of an entire landscape description (e.g. kame complex). When delta-like contours occur on slopes, rather than the basic mound outline, the term *kame delta* is sometimes applied (Price, 1973; Lundquist, 1979). The regular contour interval reflected by maps of such forms indicates that glaciofluvial sediments freely accumulated as a fan or delta without preventive obstacles (Lundquist, 1979). *Kame terraces* (flat-topped, steep-sided features) are glaciofluvial sediments that accumulated in either a marginal stream or narrow marginal lake. As deposition occurred against the ice margin, subsequent ice melting formed a steep face; the *riser* of the terrace (Price, 1973). *Kame complexes* (kame and kettle topography) are expressed as a series of kame mounds, each of which originated in its own "basin of accumulation" (Price, 1973). Clayton (1964) suggested that kames are really ice disintegration features, formed wherever cavities received water-borne sediments. As such they are distinct from *kettled sandar, kettled deltas or pitted outwash* which are landscapes developed when clean ice blocks melt out, usually in a marginal position.

Eskers are ridges composed of channel deposits, regardless of their position of formation. Sugden and John (1976, p. 330) presented four points for recognizing eskers:

a. " The longest eskers are ice-directed features which are even more accurate indicators than drumlins of the last direction of regional ice movement.

b. Eskers indicate the position of the major routes by which meltwater and fluvioglacial debris is transported from within the confines of the glacier system to achieve output at the ice margin.

c. Eskers are probably not true equilibrium forms, although the channels in which they form may have been at the time of channel formation. Eskers form only when stream velocity is falling, for example following the early summer meltwater discharge peak. Some eskers may form in tunnels in the late summer flood, as long as the containing tunnel remains in use. If a tunnel is abandoned then the esker will be able to survive as long as the glacier does not remove it.

d. The mere presence of eskers indicates free meltwater drainage towards the glacier margin. If meltwater flow is inhibited, the ice becomes saturated and channels (if they form at all) are filled with standing water. Again this may be a seasonal phenomenon; in the spring existing englacial tunnels may experience free meltwater flow in the vadose zone, but later on, during and after the discharge peak, the tunnels may find themselves well below the water table, in the zone of phreatic flow. Under these circumstances sediments are less likely to be deposited in tunnels. "

Ice-walled and ice-floored channels are basically analogous forms to eskers (Banerjee and McDonald, 1975). Crevasse-fillings, where composed of glaciofluvial sediments, are not easily differentiated from eskers although distinction may be possible by their form and structure (Sugden and John, 1976).

4.2 Glaciolacustrine Landforms and Sediments

In areas where the land sloped upward from the ice margin, retreating glaciers were often bordered by *proglacial* lakes. Such was the case with Glacial Lake Edmonton which formed in a clearly defined "lakeplain" (Shaw, 1975). However, where glacial stagnation developed (rather than systematic frontal retreat) characteristic lacustrine systems may include *superglacial* and/or *ice-walled* lakes (Clayton and Cherry, 1967). Superglacial and ice-walled lakes are differentiated with respect to their physical relationship with the stagnant ice. Both are subaerial but ice-walled lakes are distinguished

from superglacial lakes by having *bottomed* on solid ground, not ice (Clayton and Cherry, 1967).

Superglacial lake sediments have been described by many researchers of hummocky moraine regions in western Canada, northwestern U.S.A., and Scandinavia. Of particular importance for this study are observations within the Edmonton area by Bayrock and Hughes (1962), Westgate *et al.*, (1976) and Emerson (1977, 1983) plus the North Dakota observations by Clayton and Cherry (1967). The topography of collapsed superglacial lake sediments is very similar to that of collapsed superglacial till (Clayton and Cherry, 1967). A rolling, undissected topography, with abundant undrained depressions plus internal contorted or folded bedding, may be considered diagnostic criteria of collapse. Westgate *et al.*, (1976) and Emerson (1977, 1983) consistently found "superglacial marl" contained within hummocks in the Cooking Lake moraine area, Alberta. Within the study area glaciolacustrine sediments were also found mantling many till hummocks.

Ice-walled lakes were well described by Clayton and Cherry (1967). In that paper they suggested that moraine plateaux or "perched lake plains" of hummocky moraine regions owe their existence to sediments being deposited, or slumped into ice-walled lakes. They proposed that two forms of ice-walled lakes existed in single, uncoalescent basins; unstable and stable. The differentiating criteria for these two lake types are given in Table 4.4.

4.3 Glaciofluvial/Glaciolacustrine Landforms and Sediments of the Study Area

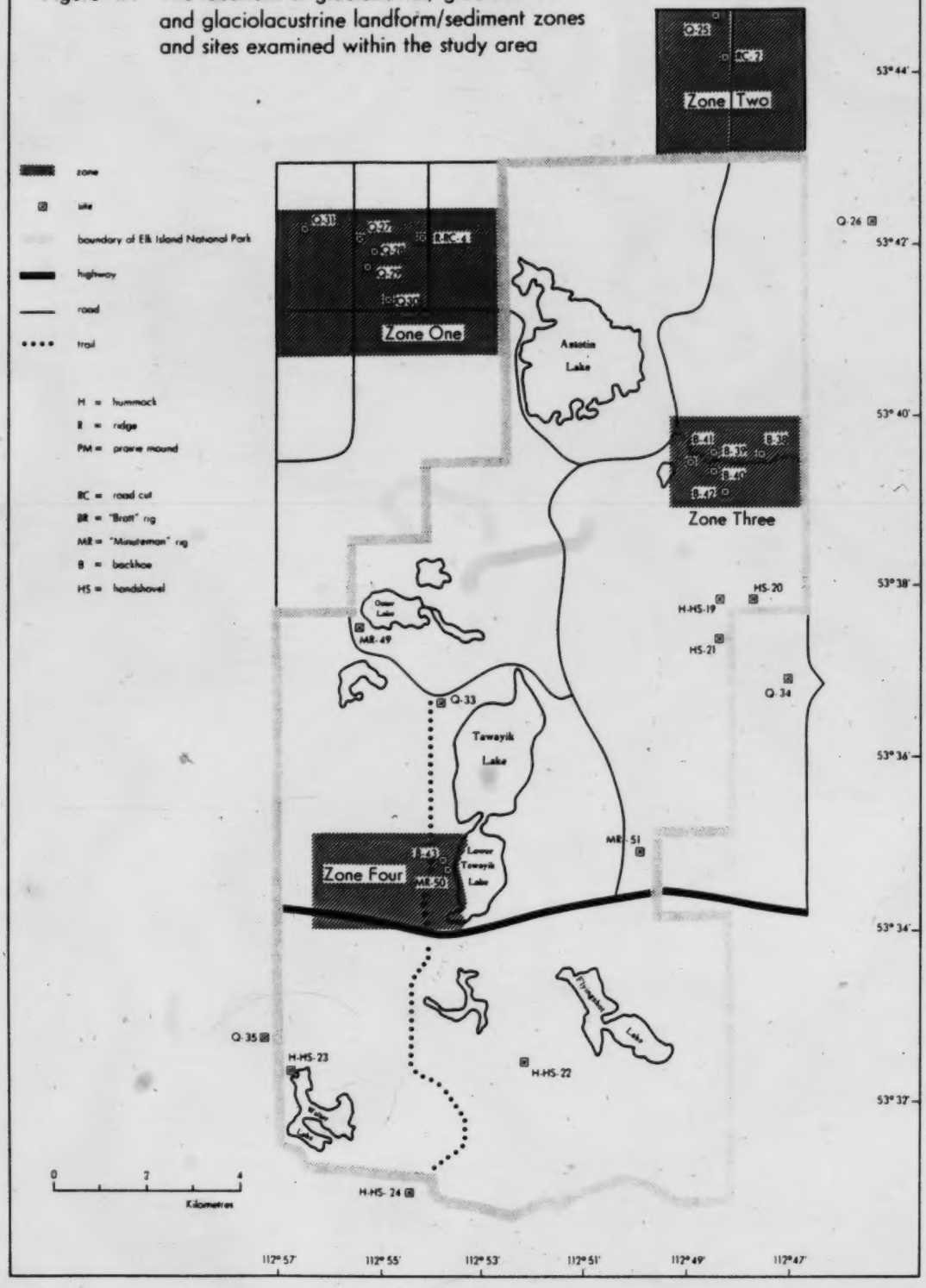
4.3.1 Introduction

Several zones within the study area exhibit landform/sediment assemblages which are interpreted as having developed within glaciofluvial, glaciodeltaic or glaciolacustrine environments (Figure 4.1). There is a continuum from zones which have till-dominated landforms thinly mantled with glaciolacustrine sediments to zones dominated by glaciofluvial/glaciolacustrine landforms. This section considers the description, interpretation and association of landform/sediment units within each major zone.

STABLE	UNSTABLE
FORMATION ENVIRONMENT:	
- develop where there is a thick superglacial debris cover	- develop where there is a thin superglacial debris cover
- high, local relief differences	- low, local relief differences
- slow melting of supporting ice	- rapid melting of supporting ice
- mass movement is limited and discontinuous	- mass movement is extensive and continuous
- much fine-grained sedimentation	- much coarse-grained sedimentation
- long-lived	- short-lived
FINAL CONFIGURATION:	
- convex-upward lake plain	- concave-upward lake plain
- found perched above surrounding landscape	- found in depressional areas
- no rims	- rims
- thick lacustrine sediments	- thin lacustrine sediments
- abundant fossils	- few fossils

Table 4.4 The criteria used to differentiate unstable and stable ice-walled lakes formed within uncoalescent basins (after Clayton and Cherry, 1967)

Figure 4.1 The locations of glaciofluvial, glaciodeltaic and glaciolacustrine landform/sediment zones and sites examined within the study area



4.3.2 Zone One; West Gate Complex

4.3.2.1 Introduction

An extensive zone of pitted and ridged terrain, composed primarily of stratified sediments (Figure 4.1) occurs in the northwestern part of the study area. Within this zone, recent quarrying and road construction provided many exposures.

4.3.2.2 Site 1; (R-RC-4)

This site is located immediately west of the park boundary (Figure 4.2). Here, recent road construction has dissected a ridge (Figure 4.3).

Observations and Interpretations of the Sediment Unit Characteristics:

In this section a fining-upward sequence of stratified units is apparent (Figure 4.4). The lowermost unit is comprised of matrix-supported cobble gravel (Figure 4.5). The subrounded/rounded clasts of varied lithologies are supported by a matrix of very coarse sand, granules and small pebbles. This unit is unconformably overlain by horizontally-laminated beds of medium/fine sand. Within the laminated sand are small pebbles and, particularly, irregular shaped masses of diamicton (Figure 4.6). The diamicton bodies have very sharp contacts with the laminated sand and they have disrupted the primary structures only slightly. The whole section is capped with a diamicton unit. Some lamination is apparent within this diamicton drape as lenses of fine-grained, bedded sediments are present.

Small-scale faulting occurs within the thick unit of horizontally-laminated sand (Figure 4.7). Reverse, high-angle faults dominate with planar displacements ranging from approximately 1.5 to 15 centimetres. At both the north and south flanks of the ridge large normal and reverse faults are apparent.

Landform Genesis:

It is believed that these sediments accumulated in a subglacial conduit. Banerjee and McDonald (1975) and Ringrose (1982) have provided a review of the literature

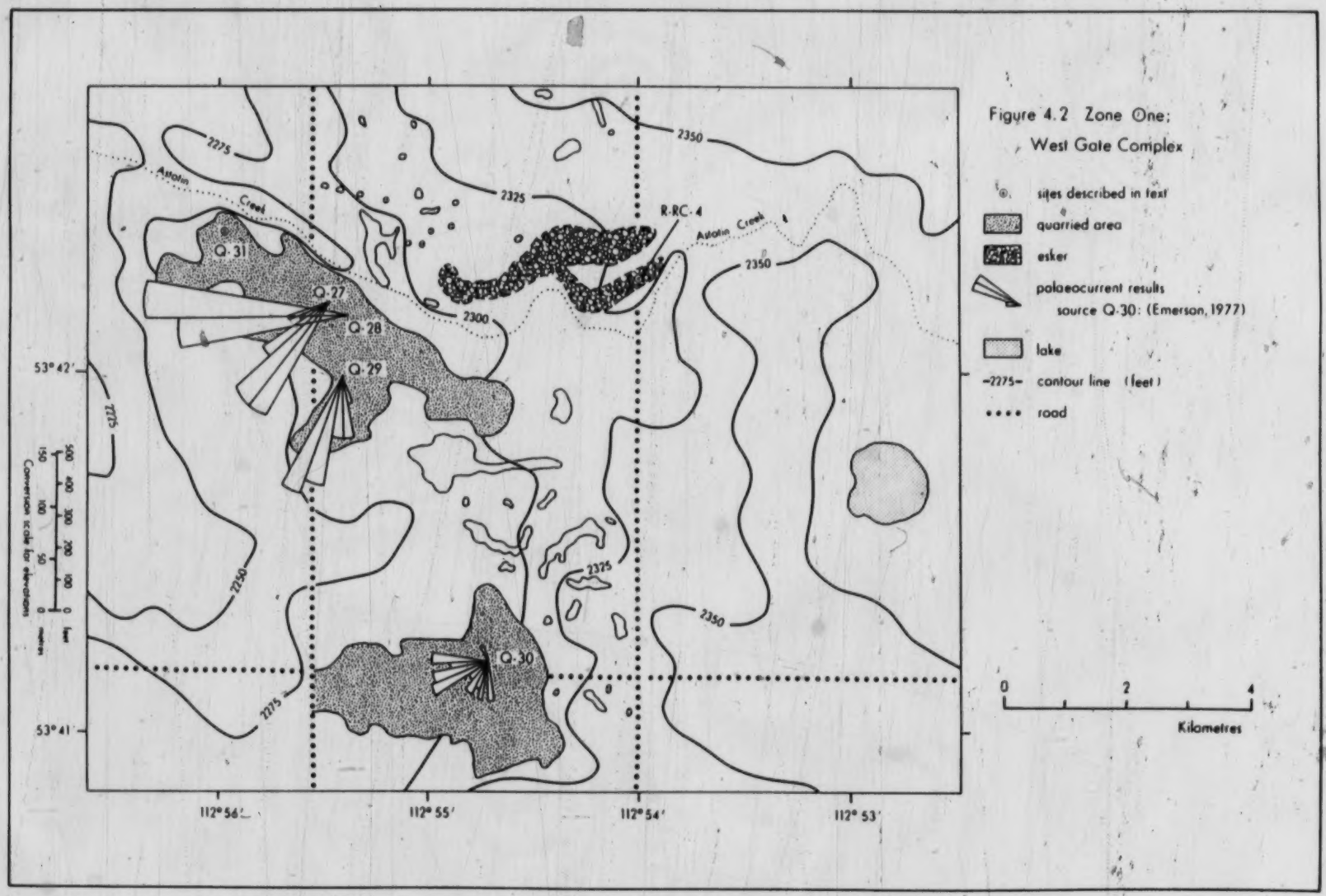


Figure 4.2 Zone One:
West Gate Complex
sites described in text
quarried area
esker
palaeocurrent results
source Q-30: (Emerson, 1977)
lake
-2275- contour line (feet)
road
Kilometres
Q-27
Q-28
Q-29
Q-30
Q-31
R-RC-4
Astotin Creek
2275
2300
2325
2350
2375
53° 42'
53° 41'
112° 56'
112° 55'
112° 54'
112° 53'
Conversion scale for elevations
metres
feet

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Figure 4.3 The external form and internal stratigraphy of ridge R-RC-4
(refer to Figure 4.4 for description)

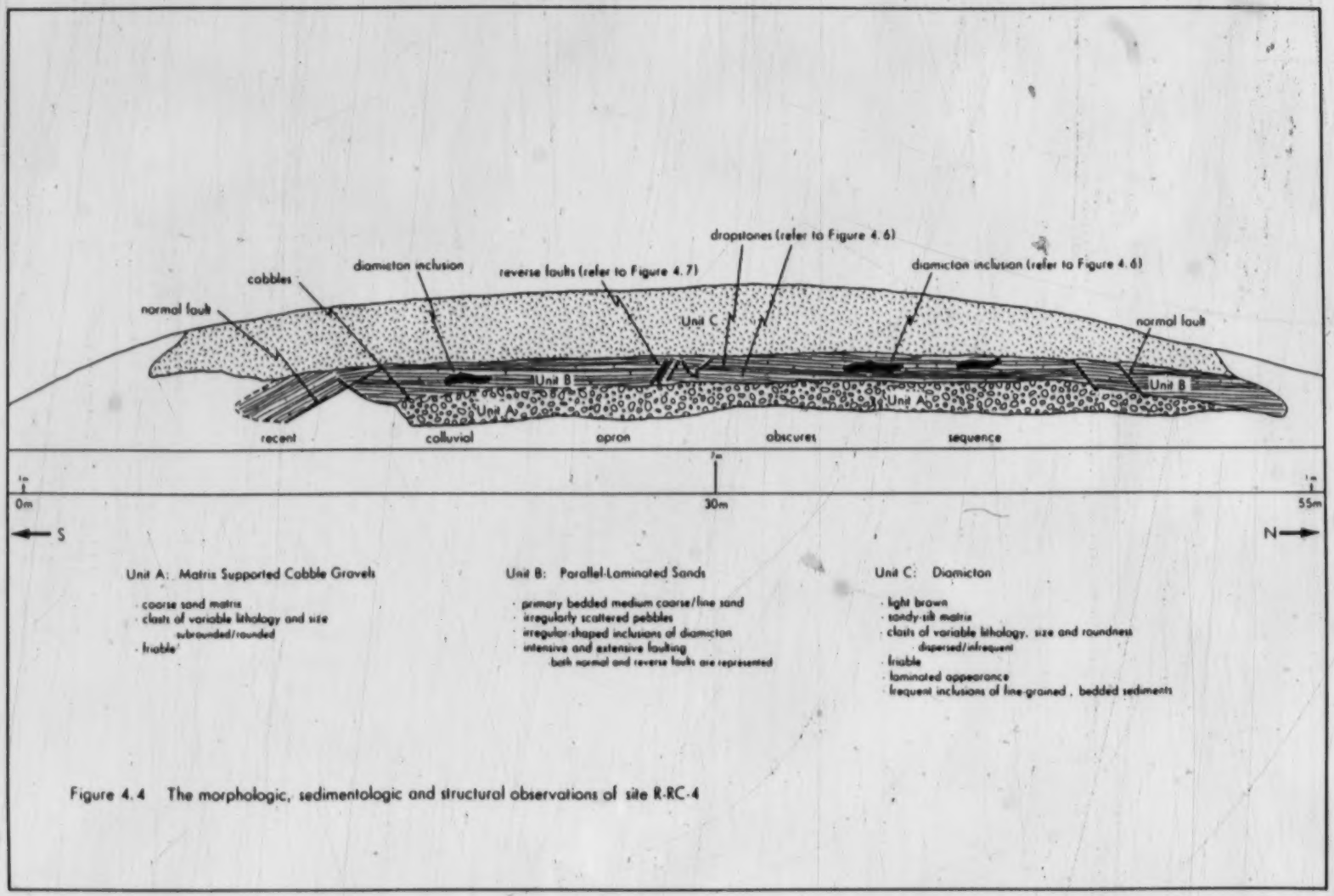

Figure 4.4 The morphologic, sedimentologic and structural observations of site R-RC-4

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Figure 4.5 The fining-upward sequence from matrix-supported gravel to horizontally-laminated beds of medium/fine sand in the central portion of ridge R-RC-4. The exposure is capped by a diamicton unit

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Figure 4.6 The irregular-shaped masses of diamicton found within the horizontally-laminated sand

Figure 4.7
The intensive small-scale faulting within the horizontally-laminated sand unit

COLOURED PICTURES
Images en couleur

pertaining to facies interpretation for both closed conduit (pipeflow) and open channel bedform development in eskers. A subglacial position need not imply a closed conduit because the tunnel may have free surface flow, an open channel situation (Banerjee and McDonald, 1975; Saunderson, 1982). Ringrose (1982, p. 127) pointed out that the "presence of any facies can rarely be regarded as diagnostic of open or closed conduit flow". For example, the proposition that matrix-supported gravels are sliding bed deposits, formed only in a closed conduit situation (Saunderson, 1977) has been challenged by Boulton and Eyles (1979). These authors found matrix-supported gravels in proximal outwash, deposited by open channel flow. Further, the system may change from a closed conduit to an open channel situation should there be tunnel expansion (roof melt or collapse) or a decrease in meltwater supply (Banerjee and McDonald, 1975). Therefore, it is not readily apparent whether or not the matrix-supported cobble gravel unit was deposited in an open or closed conduit. It can be stated, however, that high-flow regime conditions were necessary to transport the large cobbles (Shaw, 1972). A relatively confined tunnel is suggested. The cobbles represent a lag deposit, the matrix most probably having filtered in from the overlying sand unit. The abrupt transition from the cobble gravel unit to sand reflects a sudden decrease in stream competence.

Several lines of evidence complement each other for the interpretation of subglacial tunnel formation in this case. Of particular importance is the primary-bedded, horizontally-laminated sand, and its included bodies of diamicton and the numerous, isolated coarse clasts. An open channel situation, with free surface flow, was probably maintained at the site. A steady and constant flow was essential for the primary sedimentary structure. Either downstream or upstream regulation of the discharge is a possibility. Downstream, the conduit may have become choked with sediments or contricted by tunnel collapse. Further, the downstream control of the discharge may have been regulated by the presence of standing water covering the conduit exit. Alternatively, an upstream control may have been imposed as contributory moulins on the debris-covered, stagnant ice surface enlarged. The descending pipe(s) may have become filled with coarse debris, thus offering a *filtering effect* for both the amount of meltwater and the size of sediment allowed to pass into the subglacial tunnel.

The coarse clasts found scattered within the otherwise well-sorted sand probably dropped from the roof of the tunnel concurrently with primary deposition of the sands. The size and disposition of these coarse clasts within the unit exclude the possibility of normal fluvial deposition. On the basis of this interpretation these are not termed dropstones. That term applies to clasts dropped from floating ice. Similarly, the large bodies of diamicton appear to have been released from the ablating tunnel roof. These discontinuous blocks are certainly not the product of mass movement flows as little or no disturbance of the underlying sand deposits is apparent. The diamicton blocks must have been dropped, not slid, into place.

The section is capped by a diamicton unit. This may represent a sediment flow diamicton. However, a more likely alternative is that with continued ablation of the upper ice the unit was draped over the underlying beds. The presence of normal and reverse faults in the sedimentary units indicates that the slow melting of both the retaining ice walls and buried ice was probably responsible for the final ridge configuration (McDonald and Shilts, 1975; Shilts, 1981).

4.3.2.3 Sites 2, 3, 4, 5, and 6 (Q-27, Q-28, Q-29, Q-30 and Q-31)

West of Site R-RC-4 a transition from the pitted and ridged terrain to flatter topography, at a lower elevation, is apparent. On the lower topography sands gradually thin out into deep water, silt and clay deposits near the town of Josephburg. Sand and gravel quarrying activities have opened-up numerous exposures within the pitted terrain (Figure 4.2).

Observations and Interpretations of the Sediment Unit Characteristics:

At Sites Q-27 through Q-30 tabular, cross-bedded units, composed of predominantly well-sorted, sand-sized sediments were noted (Figures 4.8 and 4.9). The dip of the cross-beds varies but the average is 18°. The results of palaeocurrent measurements from each of the sites are shown in Figure 4.2. The sediments show very little penecontemporaneous or secondary deformation, with only isolated occurrences of faulting, folding and diapiric injections (Figure 4.10).

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Images en couleur

Figure 4.8 The tabular, cross-bedded sediments at Site Q-27

Figure 4.9 The tabular, cross-bedded sediments at Site Q-29

Site Q-31, at the lowest and westernmost part of the quarried area exhibits a different suite of sedimentary structures and textures. Here, the sand-dominated cross-beds are replaced by horizontally-bedded sand, silt and clay (Figure 4.11). Some of the beds (particularly those composed of silt and clay) are deformed, presumably due to loading or dewatering.

Landform Genesis:

The characteristics and distribution of sedimentary structures and textures for these sites correspond well with models of deltaic deposition. The cross-bedded sands at Sites Q-27 through Q-30 are interpreted as delta foreset beds, whereas the horizontally-bedded sand, silt and clay beds at Site Q-31 are interpreted as delta bottomsets. The spatial variation of observed palaeocurrent directions suggests that shifting distributary mouths occurred along the delta front.

The deltaic sediments were deposited into Glacial Lake Edmonton which was impounded against the ice sheet. As the ice receded to the northeast deltas were built at different localities close to the ice margin. The deltas were ice-marginal, deposited partly over ice and partly around large ice blocks standing in Glacial Lake Edmonton. The pitted nature of the topography in this zone, plus the occurrence of large bodies of diamicton within the stratified sediments at another quarry (Site Q-32; Figure 4.12), attest to the probable ice-contact situation. The water level of Glacial Lake Edmonton at the time of delta formation was at approximately 2300 feet (701 metres) a.s.l. The contact between topset and foreset beds in glaciolacustrine deltas is erosional. This erosional contact most probably is represented in Figure 4.8. Further, the similar assemblage of deltaic sediments found southwest of this zone (Site Q-32) is consistent with this interpretation (Figure 4.12).

4.3.2.4 **Summary**

Zone One illustrates the variety of deposits that may exist within an ice-contact continuum of glaciofluvial, glaciodeltaic and glaciolacustrine environments. As proposed by De Geer in 1910 (Saunderson, 1975) the lateral transition from esker gravels to

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Figure 4.10 A diapiric injection structure observed at Site Q-27

Figure 4.11 Horizontally-bedded sand, silt and clay at Site Q-31

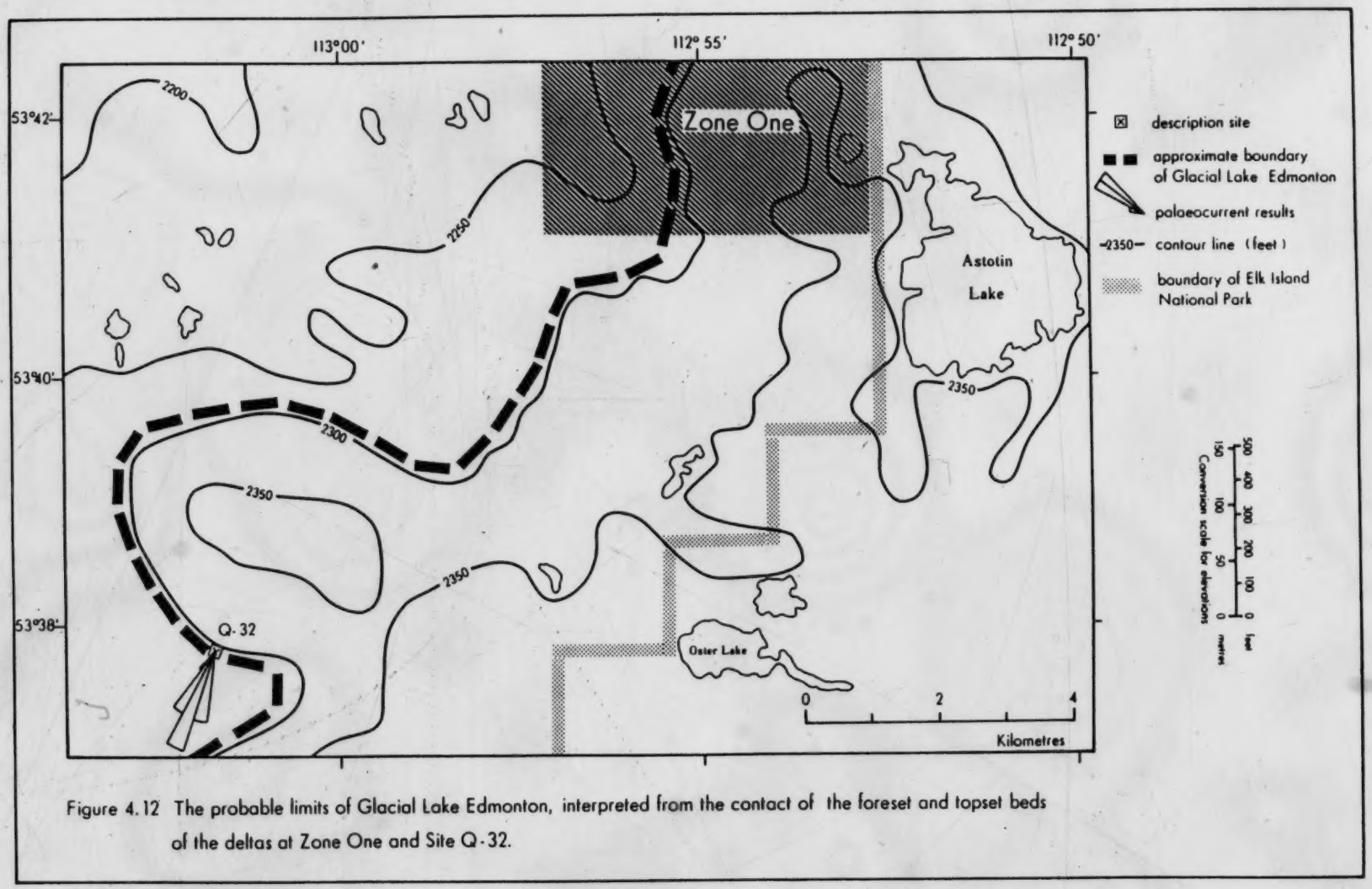

Figure 4.12 The probable limits of Glacial Lake Edmonton, interpreted from the contact of the foreset and topset beds of the deltas at Zone One and Site Q-32.

rhythmites represents different facies of the same time-stratigraphic unit. In the present example meltwater was evacuated via a subglacial tunnel which fed into a standing body of water (Glacial Lake Edmonton). Esker gravels were deposited in, or at the exit of, this tunnel. Decreasing competency of flow in the downstream direction led to progressively finer-grained sedimentation. It is possible that combinations of ice recession, rises in the water level or decreases in the sediment supply were responsible for this decreased competency (Saunderson, 1975). Further, these regulations could also explain the vertical transition from gravel to fine-grained sediments, shown at Site R-RC-4, as the facies boundaries shifted upstream.

4.3.3 Zone Two; North Gate Complex

4.3.3.1 Introduction

Zone Two occupies an area bordering the northern limit of the hummocky moraine tract and parallels the northwest-southeast trending bedrock escarpment (Figure 4.1). The area above the escarpment is rolling with numerous depressions. Below the escarpment the topography is relatively flat except for some infrequent meltwater channels (Figure 4.13). At the lower elevations bedrock is occasionally exposed near the surface (Figure 4.13, Site RC-1). Two sites of glacigenic sediments were examined in detail within Zone Two (Figure 4.13, H-RC-2 and Q-25).

4.3.3.2 Site 1 (H-RC-2)

Site 1 (H-RC-2) is located 1.9 kilometres north of the park boundary. Situated at an approximate elevation of 704 m.a.s.l., it is slightly below the upper pitted surface yet well above the lower, flatter area. At the site two small road cuts were logged (Figure 4.14).

Observations and Interpretations of the Sediment Unit Characteristics:

Section 1:

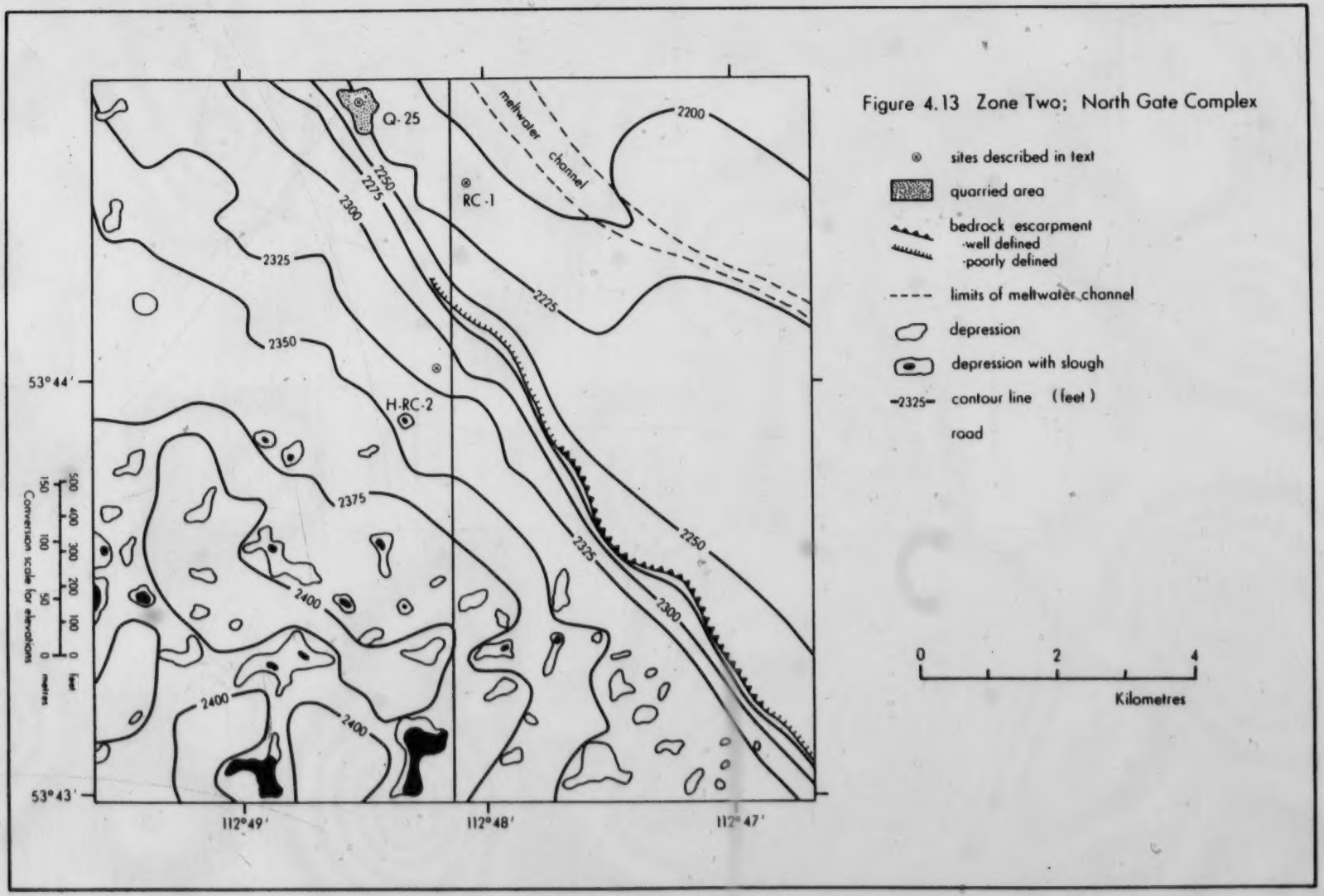

Figure 4.13 Zone Two; North Gate Complex

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Section 1 Section 2

Figure 4.14 The spatial relationship between the two sections examined at Zone Two, Site H-RC-2

A schematic description of the sedimentary units at Section 1 is given in Figure 4.15. Parallel-laminated sands and interbedded silts dominate the sedimentary sequence. Typically, a graded and repetitive sequence of silt/fine sand/medium sand/medium coarse sand/fine sand/silt is apparent. A 30 centimetre thick body of grey-brown diamicton abruptly and uncomformably interrupts the rhythmically-bedded sediment units. This vertically jointed diamicton has a silty-clay matrix enclosing clasts of varied lithologies and sizes. At one location a small cobble projected down into the stratified sediments. No groove or drag marks were associated with the cobble. This indicates that the diamicton body must have been gently lowered onto the stratified sequence. Numerous faults, which are predominantly normal, penetrate the contact between the diamicton body and stratified beds. In one case a fault was traced for the complete depth of the exposure (Figure 4.16).

Section 2:

At this section parallel-laminated sediments and multiple diamicton bodies are exposed (Figures 4.17 and 4.18). The whole stratigraphic sequence dips conformably with the slope. Normal faulting is also prominent. Numerous, small-scale faults are overshadowed by a high displacement (30 centimetres) normal fault.

At both sections, the rhythmically-deposited, parallel-laminated sediments are interpreted as lacustrine deposits. The diamicton bodies are till masses which have probably been ice-rafted into position and lowered onto the lacustrine sediments. The extensive fault structures which penetrate both the lacustrine sediments and till bodies indicate post-depositional deformation possibly due to removal of buried ice. The upper, pitted surface further attests to the presence, and subsequent melting, of buried ice.

4.3.3.3 Site 2 (Q-25)

The exposures at this site were observed and recorded in a borrow pit situated at the base of the escarpment.

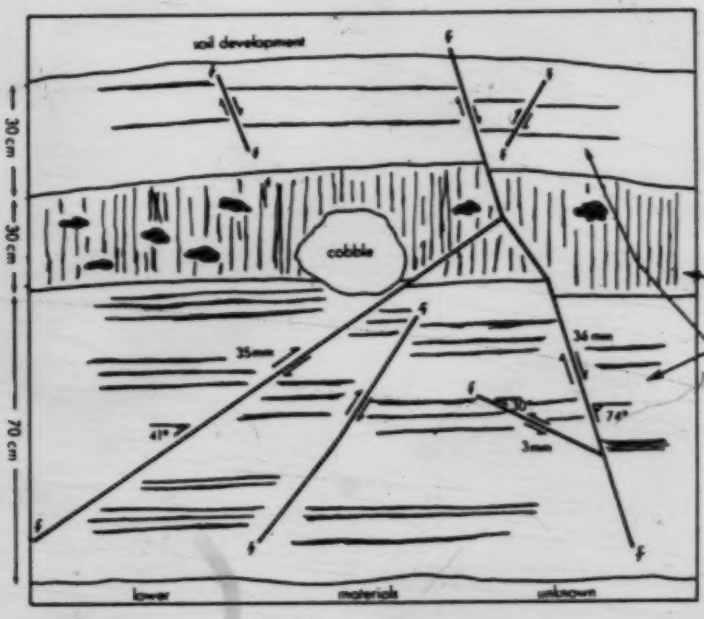

Figure 4.15
A schematic description of the sedimentologic and structural observations at Section 1, Site H-RC-2

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Figure 4.16 Numerous faults, which are predominantly normal, penetrate the contact between the diamicton body and stratified beds

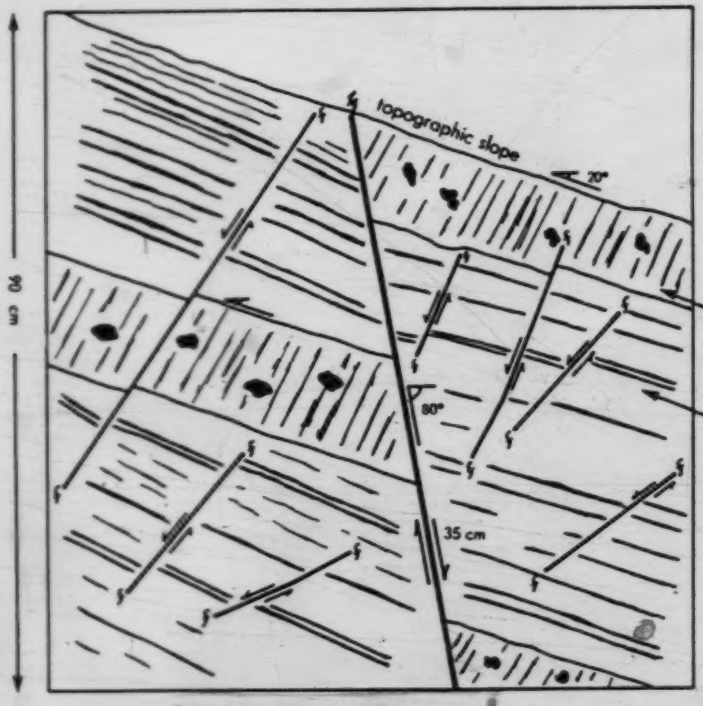

Figure 4.17

A schematic description of the sedimentologic and structural observations at Section 2, Site H-RC-2

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Figure 4.18

Parallel-laminated sediments and multiple diamicton bodies are expressed at Section 2, Site H-RC-2

Observations and Interpretations of the Sediment Unit Characteristics:

The generalized sedimentary sequence, which is a composite of several exposures, has a variable thickness of sorted sand and gravel overlain by parallel and rhythmically-bedded sands and silts. The sand-dominated rhythmites (Figure 4.19) are commonly deformed by normal, high-angle faults (Figure 4.20).

The general trend of progressively finer-grained sediments higher in the section is attributed to a diminished sediment source, hence a retreat of the glacier. Thus the sedimentary sequence is interpreted as proximal outwash deposits overlain by more distal lake sediments. The post-depositional fault structures, as at Site 1, are possibly due to subsequent removal of buried ice.

4.3.3.4 **Summary**

The deposits of Zone Two record the sedimentation phases in an ice-dammed lake environment as the main ice mass retreated to the northeast. While the ice retreated from the area, meltwater was impounded between the ice mass and the bedrock escarpment at progressively lower elevations (Figure 4.21). The gradational retreat allowed proximal sediments to become overlain by distal, fine-grained sediments. The non-sorted sediments (diamicton) represent deposition from ice-rafted blocks which broke free and floated into place. These ice bergs were blown by the prevailing north-northwest winds and accumulated in an embayment between the glacier and the escarpment (Figure 4.21). All deposits accumulated over buried, stagnant ice.

Rapid retreat of the glacier is envisioned. Consequently, the lake environment was short-lived and not extensive in the area. This is indicated by the nearby occurrence of a thin till mantle over bedrock to the north. Shallow meltwater channels evacuated the meltwater as the ice retreated quickly and a larger area opened up.

4.3.4 Zone Three; Old South Boundary Complex.

Figure 4.19
The thick sand-dominated rhythmites at Site Q-25

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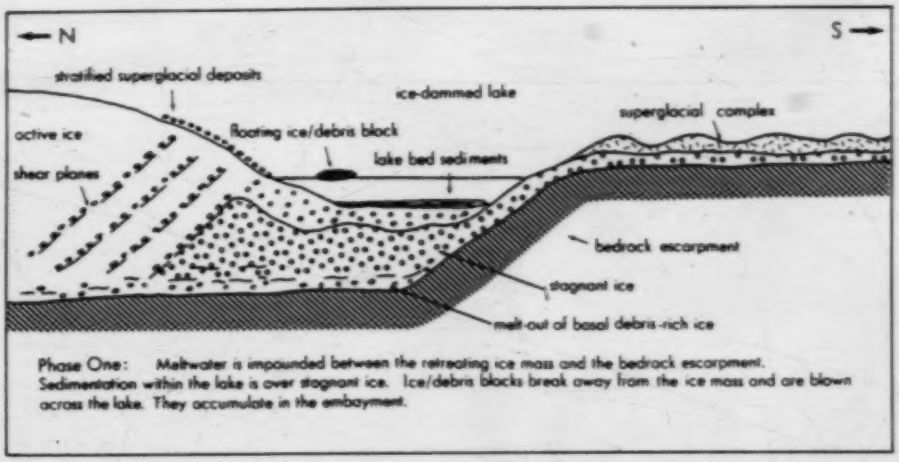
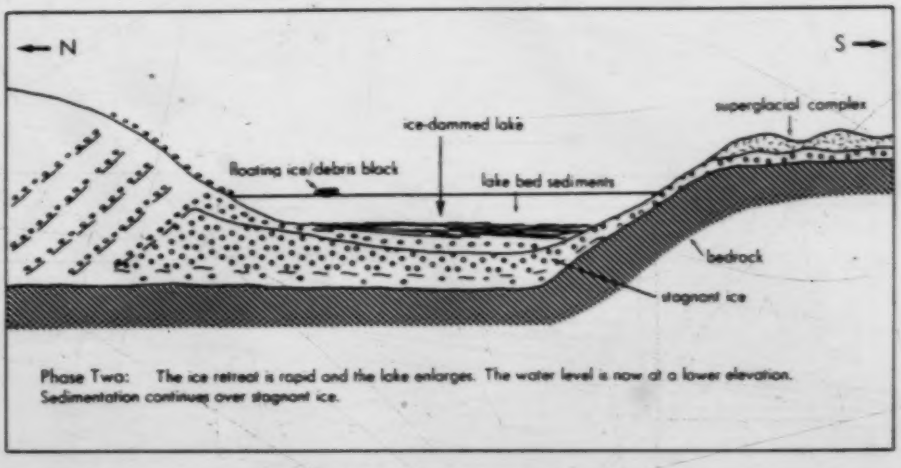
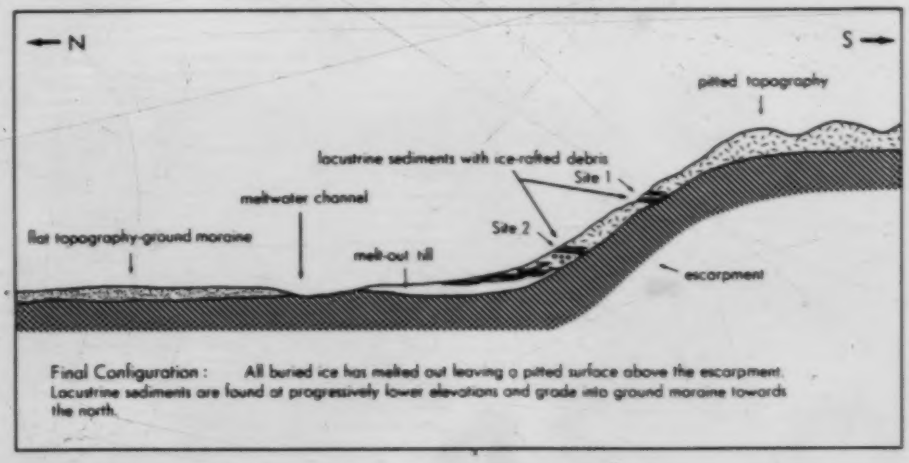
Figure 4.20 The high-angle, normal faults within the rhythmites at Site Q-25



Phase One: Meltwater is impounded between the retreating ice mass and the bedrock escarpment. Sedimentation within the lake is over stagnant ice. Ice/debris blocks break away from the ice mass and are blown across the lake. They accumulate in the embayment.



Phase Two: The ice retreat is rapid and the lake enlarges. The water level is now at a lower elevation. Sedimentation continues over stagnant ice.



Final Configuration: All buried ice has melted out leaving a pitted surface above the escarpment. Lacustrine sediments are found at progressively lower elevations and grade into ground moraine towards the north.

Figure 4.21 The suggested formation phases for Zone Two

4.3.4.1 Introduction

Zone Three is located southeast of Astotin Lake (Figure 4.1). Access to the zone is provided by the *Old South Boundary* road which bisects the zone (Figure 4.22). The topography is variable and includes low-relief hummocks and broad, shallow depressional areas in the western portion. To the east, high-relief hummocks are separated by deep, narrow depressions (Figure 4.23). The changes in topography are are mainly a reflection of the surficial deposits and the landscape genesis.

Backhoe excavations (Figure 4.22), selected on the basis of accessibility, revealed landforms consisting largely of stratified sediments to the west and morainic landforms to the east. The first group occupies the higher areas. The stratigraphy at each of these backhoe excavation sites is briefly discussed and interpreted.

4.3.4.2 Site 1 (B-41)

At Site 1 (Figure 4.22) a 4 metre thick diamicton unconformably overlies an intensely deformed unit of sorted medium and coarse sands (Figure 4.24). The contact between the two units is both sharp and planar (Figure 4.25). The sandy silt diamicton is poorly consolidated, mottled, and has a faintly laminated structure. The sorted sands have no apparent primary structure. They have been intensely deformed and it is impossible to determine their original configuration. The diamicton is interpreted as a sediment flow diamicton. The sorted sands are probably glaciolacustrine sediments.

4.3.4.3 Site2 (B-39)

At this backhoe excavation (Figure 4.22) a similar stratigraphy was noted (Figures 4.26 and 4.27). Five units were identified in the 4.2 metre section. All units dipped conformably at approximately 21° towards the southwest (230°). The lowermost unit consists of thinly laminated silt and fine sand. The thickness of each of the parallel laminations was approximately 1 millimetre. Unit B is a deformed (contorted and faulted) deposit of sand, silt and clay (Figures 4.28 and 4.29). Unit C is a silty-clay diamicton with faint lamination. Unit D consists of parallel-bedded sand and silt. Some elongate, coarse sand lenses are also conformably bedded. These sand lenses tend to pinch out laterally. A

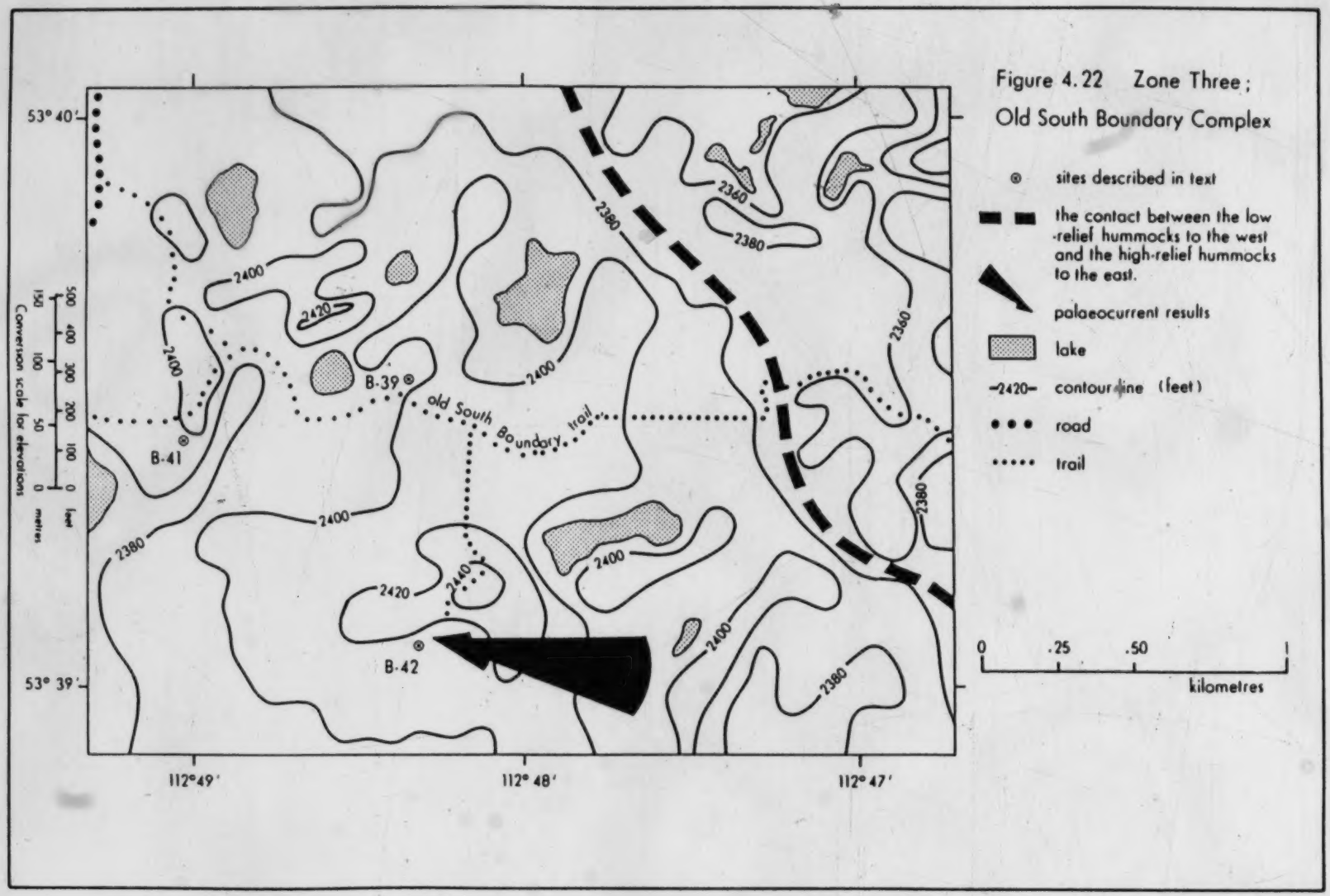


Figure 4.22 Zone Three; Old South Boundary Complex

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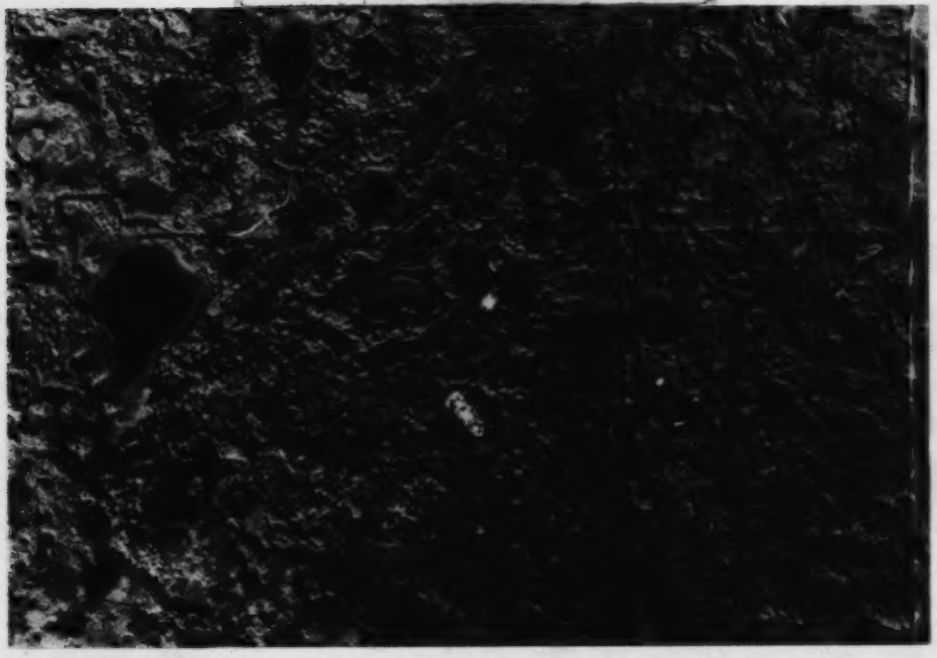

Figure 4.23 The low-relief hummocks to the west contrast with the high-relief hummocks to the east

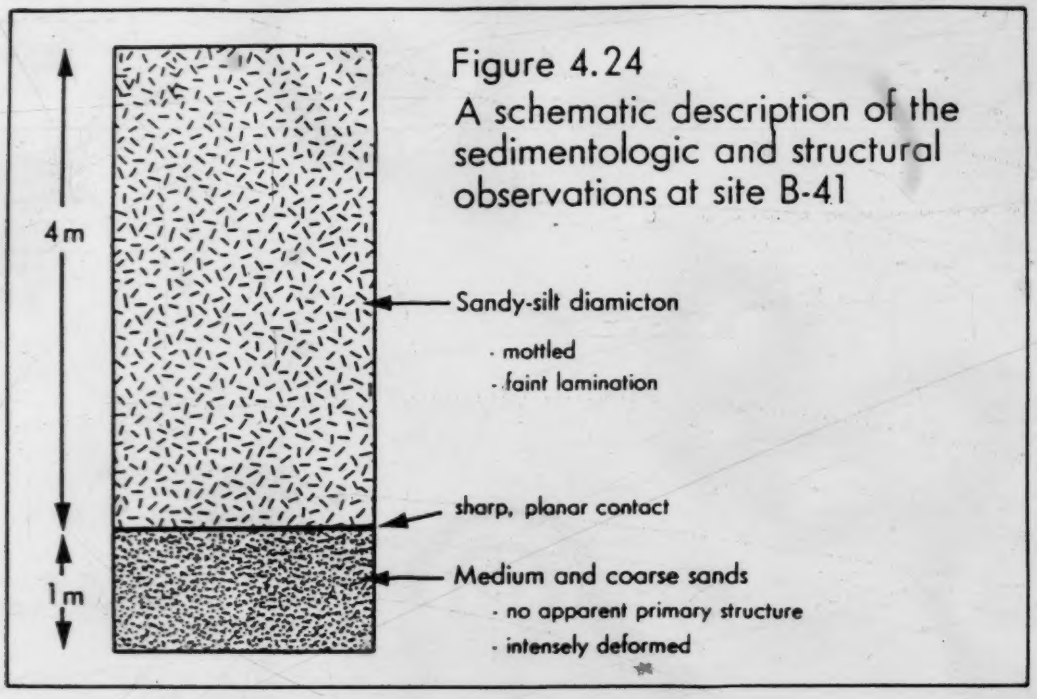

Figure 4.24
A schematic description of the sedimentologic and structural observations at site B-41

Figure 4.25 The contact between the two units depicted in Figure 4.24

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Figure 4.26 The backhoe excavation at Site B-39
(refer to Figure 4.27 for description)

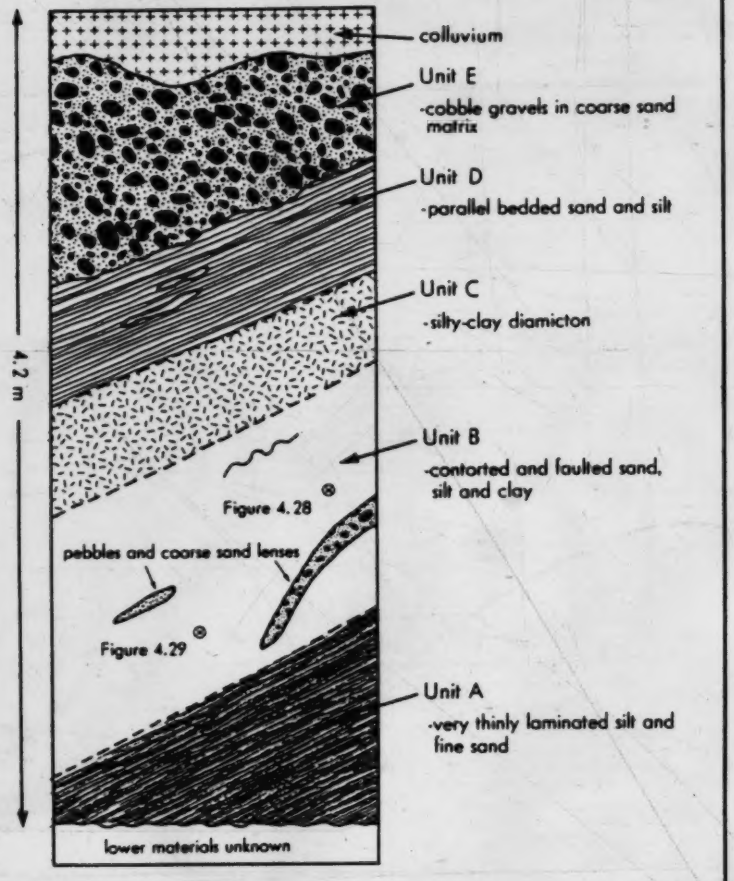

Figure 4.27 A schematic description of the sedimentologic and structural observations at Site B-39

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Figure 4.28 The deformation structures observed within Unit B at Site B-39

Figure 4.29 The deformation structures observed within Unit B at Site B-39

poorly sorted unit of angular and subrounded cobble gravel, in a coarse sand matrix, caps the section.

Units A, B and D are interpreted as lacustrine sediments deposited in a superglacial pond. Unit C is a sediment flow diamicton which both interrupted sedimentation and contorted the sediments of unit B. The tilted strata, faulting and diamicton bodies are indicative of deposition in an ice-contact environment. Gravitationally-induced collapse of the ablating ice below these deposits probably produced the normal faulting.

4.3.4.4 Site 3 (B-42)

At Site 3 (B-42; Figure 4.22) the backhoe excavation was hindered by groundwater flow which filled the hole quickly and caused slumping of the banks. Accordingly, the information on sedimentological succession is restricted to the upper few metres only. The exposed sedimentary sequence at Site 3 is given in Figures 4.30 and 4.31. Two main units are depicted. The lower unit consists of planar beds of alternating fine sand and silt dipping at 26°. A single palaeocurrent measurement records a flow direction towards the east (Figure 4.22). This unit is succeeded by a unit of large-scale, cross-bedded, coarse sand and granules. The cross-bedding is closely linked to cut and fill structures. The meagre sedimentary information indicates a small delta. Unit A could possibly be interpreted as foreset beds and Unit B as topset beds. This delta probably built into a superglacial or ice-walled pond.

4.3.4.5 Summary

The ice-contact environment, in which these sediments were deposited, was unstable. The stratigraphy expressed at these sites is consistent with published information on kames (see Holmes, 1947; Price, 1973; Sugden and John, 1976). Superglacial depressions, possibly formed in the glacier *pseudo-karstic* manner described by Clayton (1964), became basins for accumulation of pond sediments. Meltwater may have entered from more than one direction forming small deltas. At the same time superglacial debris slid or slumped into these depressions mixing and modifying the pre-existing sediments. When these settling basins became choked with debris, water burst into the adjacent depressions. Relief inversion dictated the final configuration as

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Figure 4.30 The sedimentary sequence exposed at Site B-42

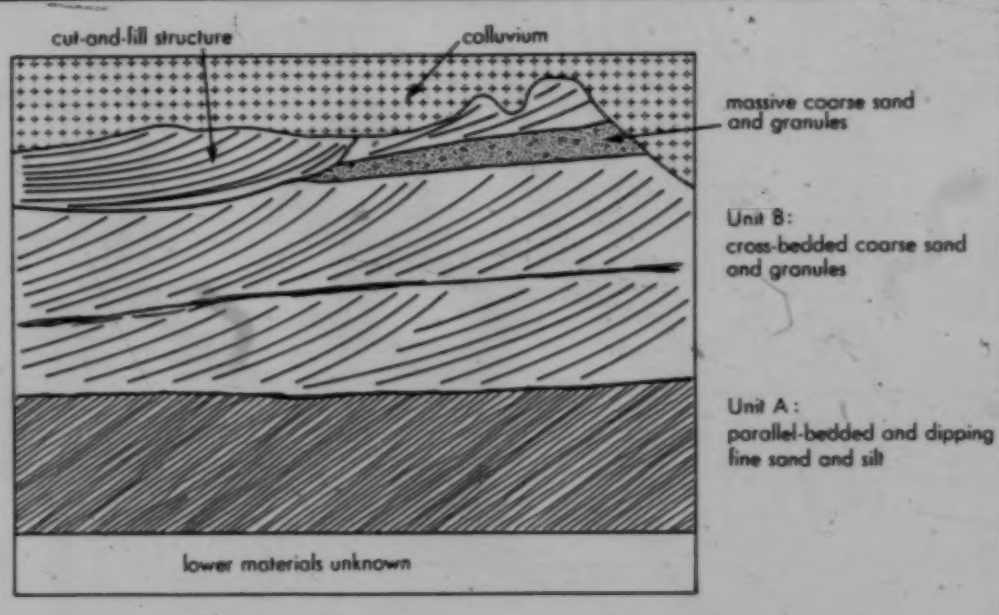

Figure 4.31 A schematic description of the sedimentologic and structural observations at Site B-42

buried ice ablated.

4.3.5 Zone Four; Lower Tawayik Lake Complex

4.3.5.1 Introduction

Zone Four, located immediately west of Lower Tawayik Lake (Figure 4.1), is a complex zone illustrating contrasts in surface topography and surficial deposits (Figure 4.32). In the western part of this zone the landscape exhibits high-relief ridges and hummocks. The landforms are till-dominated. A lower elevation, gently undulating topography separates this area from the still lower, contemporary, Lower Tawayik Lake depression. Lacustrine sediments mantle the lowest exposed surface. Of particular interest is the contact zone between the two landscapes. Aerial photograph interpretation revealed an area which was originally cleared for sand and gravel quarrying. In this area two sections were excavated using a backhoe.

4.3.5.2 Site 1 (B-43)

The site, no longer in active quarrying use, has an undulating topography and the surface is strewn with boulder-sized debris. The surface elevation ranges between 722 metres a.s.l. and 725 metres a.s.l. The contemporary water level of Lower Tawayik Lake is 715 metres a.s.l.

The two adjacent backhoe excavations, 300 metres west of the lake margin, exposed the subsurface stratigraphy. Because each excavation yielded different sedimentary structures a trench linking the two was dug to determine the nature of the contact between these differing sequences (Figure 4.33). In addition, a borehole was drilled immediately adjacent to the excavations using the small *Minuteman* auger. Penetration was to a depth of 7 metres below the surface, the maximum drilling capability of the rig.

Observations and Interpretations of the Sedimentary Unit Characteristics:

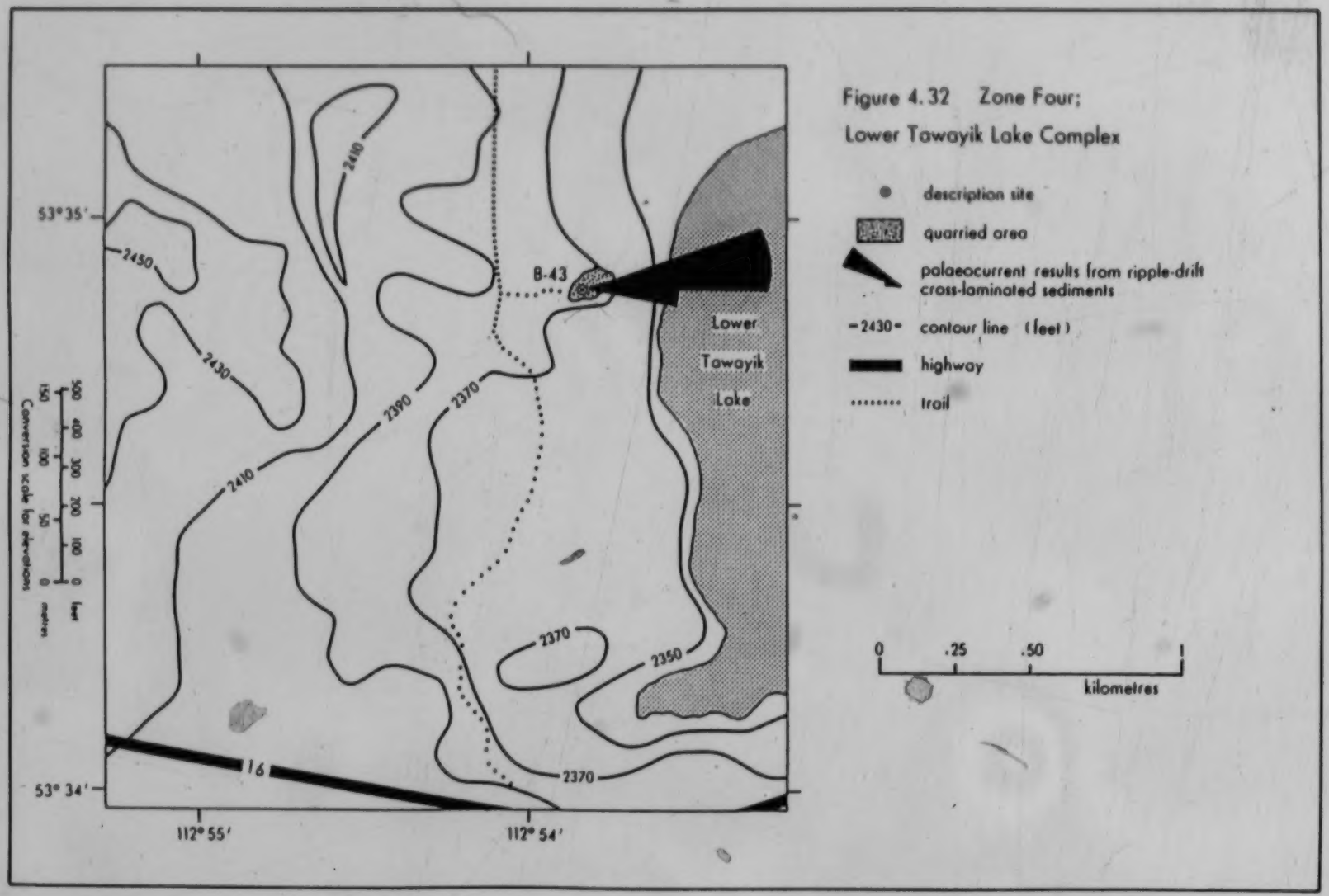

Figure 4.32 Zone Four;
Lower Tawayik Lake Complex

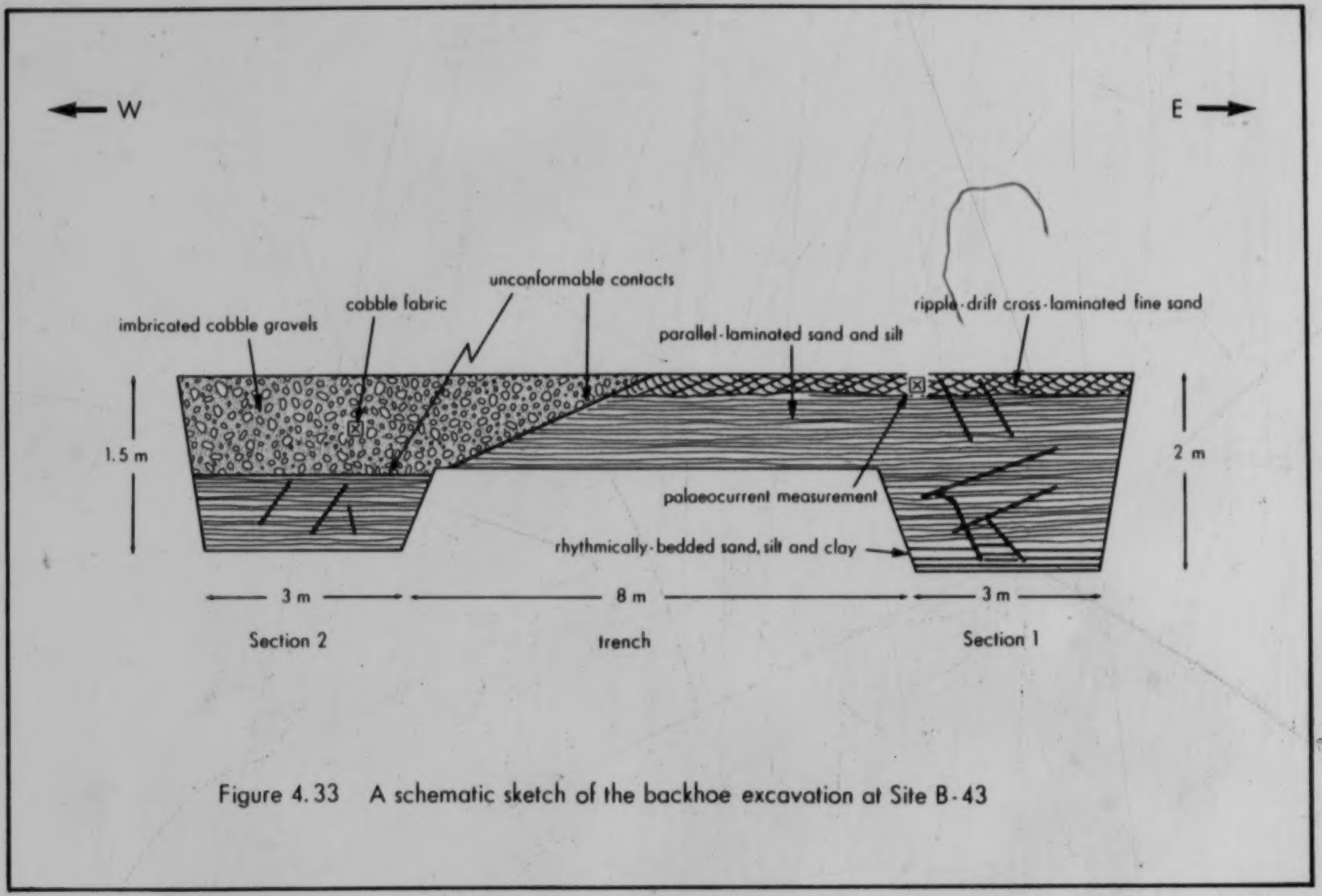

Figure 4.33 A schematic sketch of the backhoe excavation at Site B-43

There are three sedimentary units at Section I, each characterized by variations in texture and sedimentary structures. The lowermost unit consists of rhythmically-bedded sand and silty-clay; the intermediate unit is composed of parallel-laminated sand and silt and the upper unit includes ripple-drift cross-laminated fine sand (Figures 4.34 and 4.35). Section 2 exhibited two units; a thin basal unit of parallel-laminated fine sand and silt (analagous to the intermediate unit at Section 1), and an upper unit of poorly sorted, well-imbricated cobble gravel (Figure 4.36). The sedimentary structures and textures are here described separately for each unit. As well, the depositional processes are interpreted. Finally, the spatial and temporal relationships between the units are interpreted to provide a palaeoenvironmental model.

Section 1, Unit A; Rhythmically bedded sand and silty-clay:

This lowermost unit consists of a repetitive sequence of grey silty-clay interbedded with medium sand. The silty-clay beds are approximately 4 centimetres thick and the sand beds approximately 10 centimetres. The upper contact is gradational into Unit 2. Below the exposed level of Section 1 the borehole record shows a general fining-downward sequence from silt to clay. Within this unit deformation is restricted to normal faulting. The displacements are mainly linear although occasionally low-angle, concave-downward faults are recognized. Displacement is generally less than 10 centimetres.

The sediments of Unit A most probably represent bottomset beds of a prograding delta. The rhythmite bedding is the result of deposition by turbidity currents during early stages of lake filling. Jopling and Walker (1968), Gustavson *et al.*, (1972), Ashley (1975), Gustavson *et al.*, (1975), Theakstone (1976) and Shaw (1977b) all suggested that density underflows or bottom turbidity currents should be the major mechanism responsible for rhythmic sedimentation in proximal lake-bottom sediments (bottomset beds). Pulsating turbidity currents occur, whereby incoming sediment-laden water (having a higher density than the ambient lake water) sink and flow along the bottom. These are capable of deposition in cycles (Leckie and McCann, 1982).

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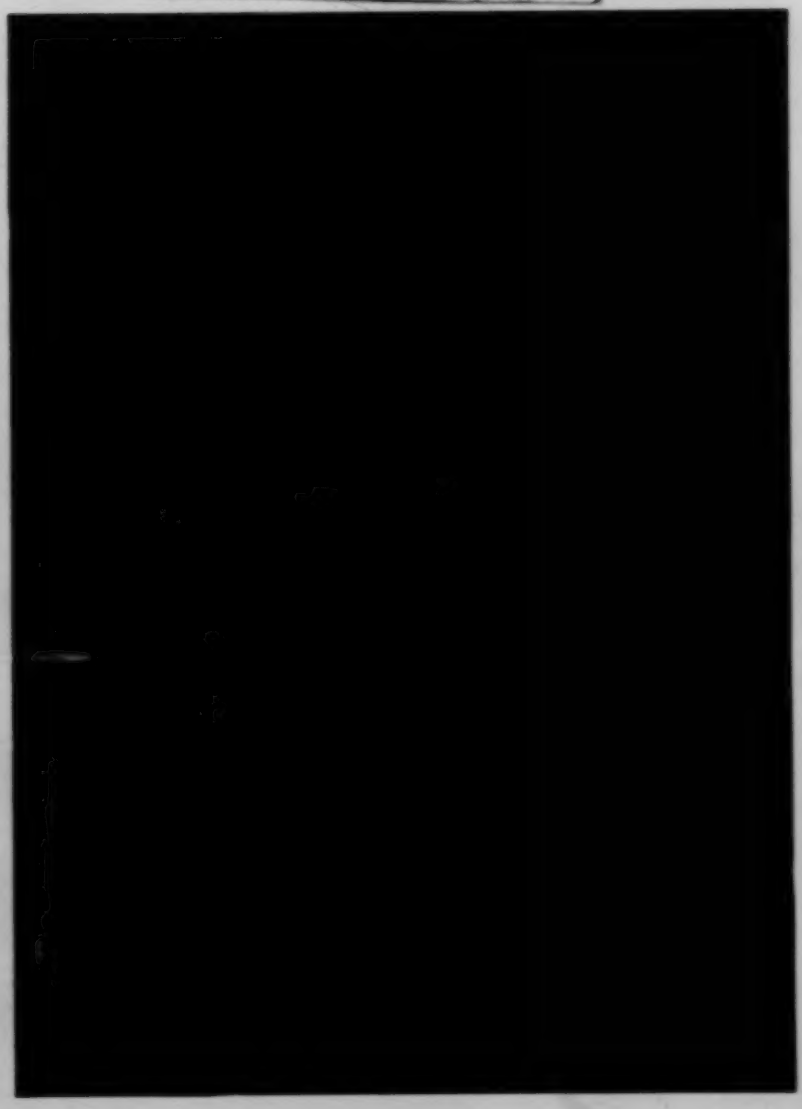

Figure 4.34 The stratigraphy of Site B-43, Section 1
(refer to Figure 4.35 for description)

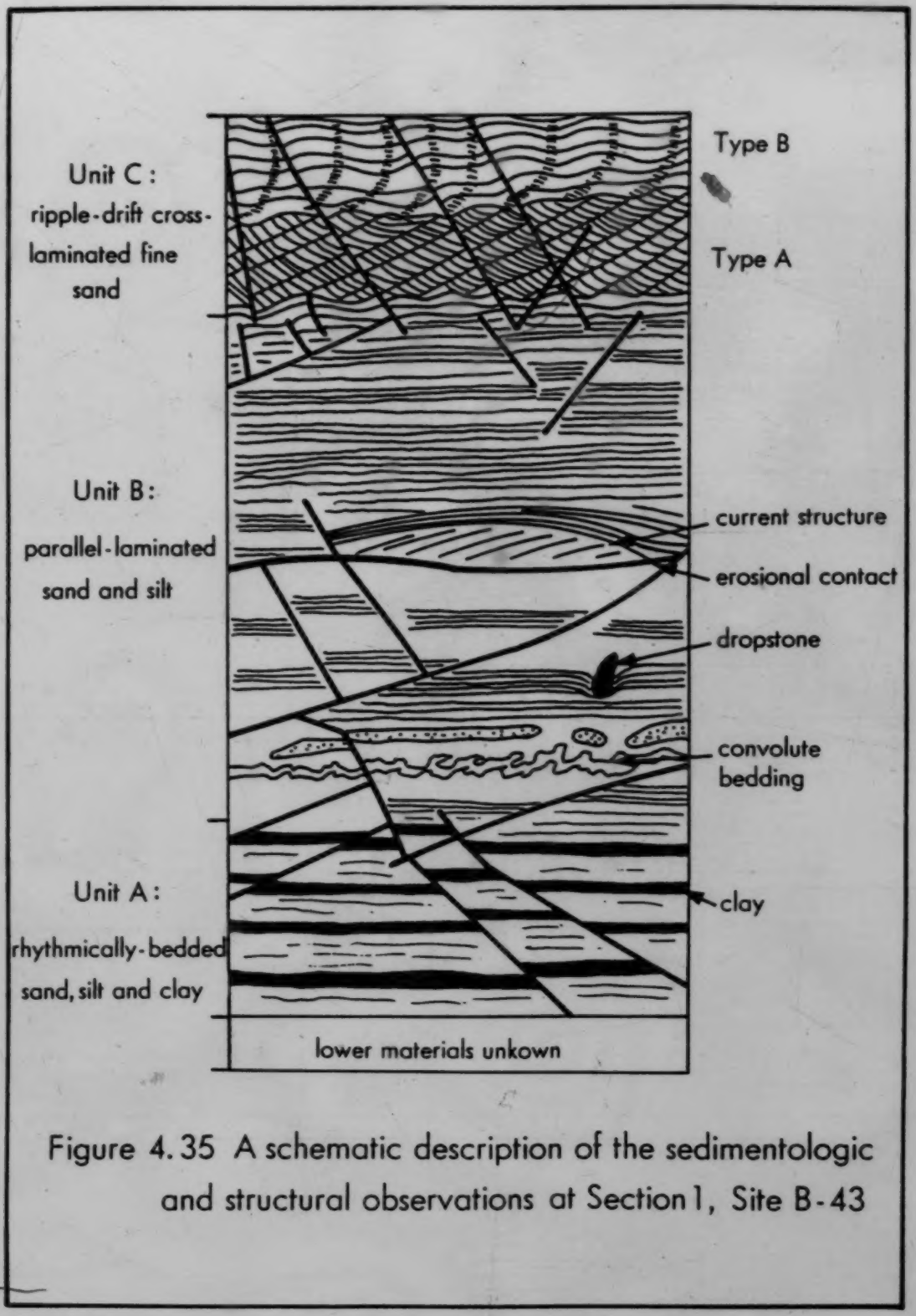

Figure 4.35 A schematic description of the sedimentologic and structural observations at Section 1, Site B-43

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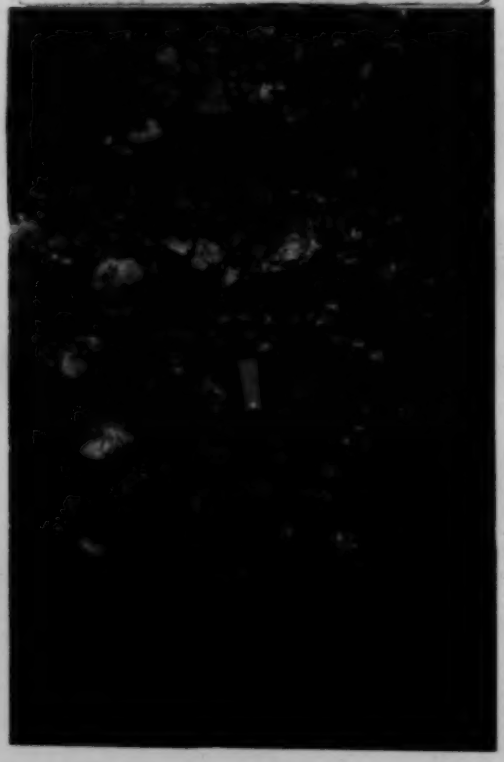

Figure 4.36 The stratigraphy of Site B-43, Section 2

Section 1, Unit B; Parallel-laminated fine sand and silt:

Unit B consists primarily of parallel-laminated fine sand and silt. The upper contact is again gradational into Unit C. The original primary bedding has been highly deformed in many instances. Each of the deformed bedsets is underlain and overlain by undisturbed parallel strata. These penecontemporaneous deformations (Figure 4.35) include convoluted bedding, an erosional feature and dropstone-induced deformation (Figure 4.37). Secondary structures are again represented by intensive faulting.

The deformation structures are of particular importance. The convoluted bedding is probably the result of low-angle, subaqueous slumping (Leckie and McCann, 1982) resulting from compaction of lake sediments. Post-depositional consolidation may also account for the step and graben micro-faulting. The erosional feature in the parallel-laminated sediments attests to the presence of current action which eroded the base of the structure, transported the sand up the stoss side of the form and dumped it down the lee side. The current direction responsible for its construction was from west to east. Finally, the weathered clast in this unit was obviously ice-rafted since there is recognized disturbance and warping of the underlying beds.

Section 1, Unit C; Ripple-drift cross-laminated fine sand:

This unit consists of a transitional sequence from type A ripple-drift cross-lamination at the base through low climb-angle type B and finally high climb-angle type B ripple-drift cross-lamination (Figures 4.35 and 4.38). This unit is also riddled with faults although no penecontemporaneous deformation is apparent. The ripple-drift cross-lamination offered the only opportunity to measure the flow direction from which the fine-grained sediments were deposited. The results are depicted in Figure 4.32.

This sequence of ripple-drift cross-lamination is particularly informative as to the flow characteristics during its formation. Ripple-drift cross-laminations are common in fine-grained deltaic deposits (Ashley *et al.*, 1982) and their field descriptions and interpretations from glaciolacustrine deltas are numerous (see Jopling and Walker, 1968; Shaw, 1972, 1975; Gustavson, 1975; Gustavson *et al.*, 1975; Orombelli and Gnaccolini,

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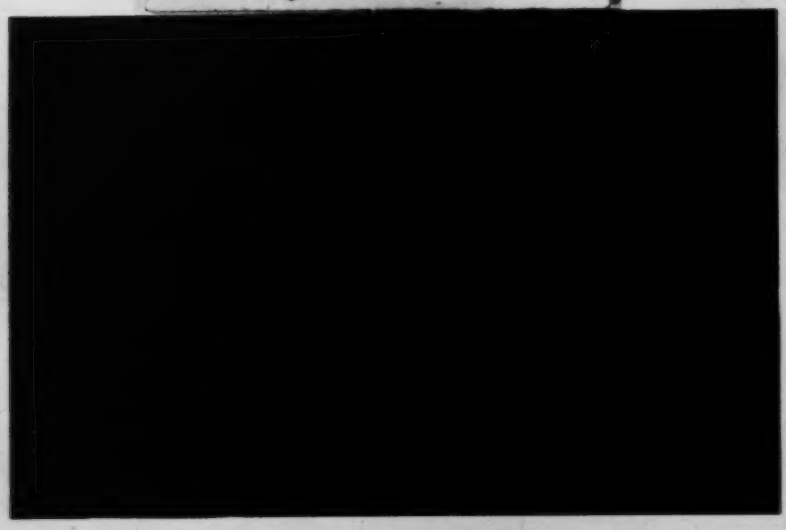


Figure 4.37 The penecontemporaneous deformations within Section 1, Unit B

Figure 4.38 The ripple-drift cross-laminated fine sand of Section 1, Unit C

1978; Cohen, 1979; Clemmenson and Houmark-Nielson, 1981). Such cross-laminations are best developed in environments of periodically rapid accumulations of fine-grained sediments (Reineck and Singh, 1975) and often originate from density underflows of sediment-laden meltwater flowing into a glacial lake (Jopling and Walker, 1968). The flow must be high enough for ripple migration yet not so high as to produce dunes or planar beds (Ashley *et al.*, 1982). The differences between the two major morphologic types are attributed to small fluctuations in current velocity, and to variations in composition and concentration of suspended load. Type A ripple-drift cross-laminations (eroded stoss) are produced by aggradation rates which are large relative to ripple migration rates (Ashley *et al.*, 1982). Jopling and Walker (1968) and Gustavson *et al.*, (1975) interpreted a change from type A to type B to be the result of a decrease in density underflow velocity and a corresponding decrease in bedload transport relative to fallout from suspension. Simply, if enough sediment is available in suspension, almost no erosion of the stoss-side takes place. The ripples are completely buried and preserved under a suspension-deposited sand cover which is again rippled but with slight drift of the crests (Reineck and Singh, 1975).

The angle of climb for ripple-drift cross-laminations has also been used to reconstruct flow conditions during deposition (see Jopling and Walker, 1968; Allen, 1971; Shaw, 1975; Gustavson *et al.*, 1975; Cohen, 1979; Ashley *et al.*, 1982). Allen (1971) noted that an increase in the ratio of sediment falling out of suspension to the rate of deposition as bedload would cause an increase in the angle of climb.

The vertical transition of ripple-drift cross-laminations noted in this section is analogous to the sequence described by Gustavson *et al.*, (1975) as a single flow event. The type A ripple-drift cross-laminations represent the maximum flow velocity. Deceleration of flow is depicted by the transition to type B and finally to an increase of climb-angle of the type B ripple-drift cross-laminations.

Section 2, Unit D; Cobble Gravels:

The upper unit at Section 2 contrasts sharply in textural qualities to the other units described at this site. This imbricated cobble gravel has a matrix of very coarse, angular

sand and granules. The clasts are dominantly subrounded to well-rounded Cordilleran quartzites although Canadian Shield clasts are also represented. The contact with the underlying unit is sharp and planar. The erosional contact between this sedimentary sequence and that of Section 1 is also unconformable, planar and dips at an angle of 23° towards the west. The laminated fine sands and silts of Section 1, Unit B, are abruptly truncated (Figure 4.39). A pebble fabric, using the a/b plane imbrication of the cobbles, indicated a strong, unidirectional, northeast flow direction (Figure 4.40).

This unit is interpreted as glaciofluvial sediments, deposited from a channel which eroded into the pre-existing sediments. The textural attributes and lack of cross-bedding suggest deposition at a location fairly proximal to the source (Leckie and McCann, 1982). The different palaeocurrent direction to the one measured for the ripple-drift cross-lamination sequence suggests that the meltwater source had changed slightly.

4.3.5.3 **Summary**

In general terms the sedimentary structures expressed at this site indicate deposition in an ice-contact environment. The proximity to an ice margin makes it difficult to differentiate glaciofluvial, glaciodeltaic and glaciolacustrine environments. However, each of the units described provided clues to the dominant depositional processes and hydrodynamic conditions.

Interpretations of the primary, penecontemporaneous and secondary structures suggest that these sediments accumulated on a low slope, prograding delta. The gently shelving lake was most probably ice-walled and ice-floored (Figure 4.41, Stage 1).

The primary structures indicate that most of the observed fine-grained sediments accumulated on the distal prodelta slope and are approximately equivalent to bottomset beds. Some penecontemporaneous structures are current-induced while others are the result of differential compaction, loading, subaqueous slumping or ice-rafting of debris. The secondary structures may be attributed to differential compaction, dewatering or release of ice support.

COLOURED PICTURES
Images en couleur

Figure 4.39 The erosional contact between Section 1, Unit B and Section 2, Unit D

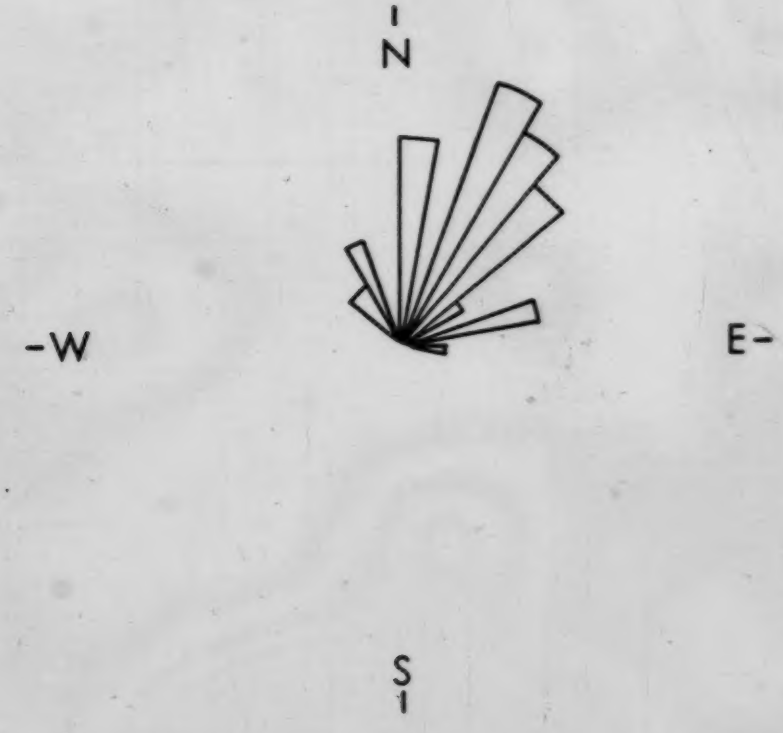
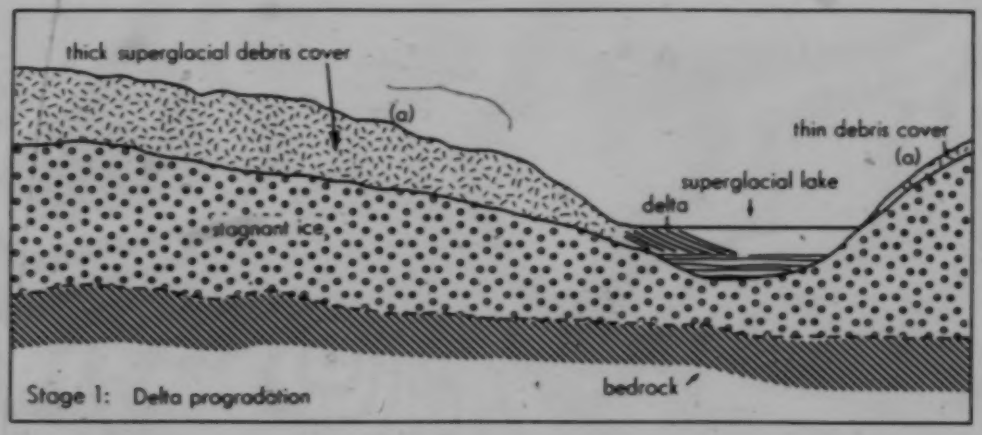
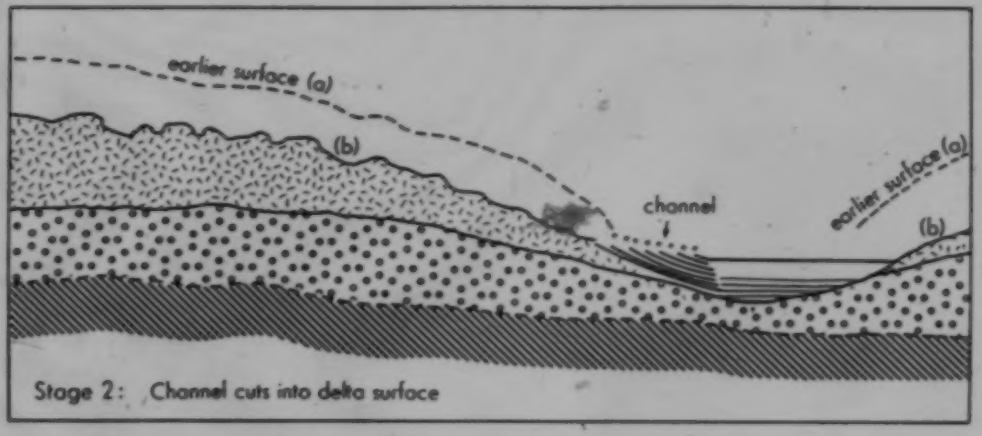


Figure 4.40 The palaeocurrent results from the a/b imbrications of cobbles at Section 2, Site B-43





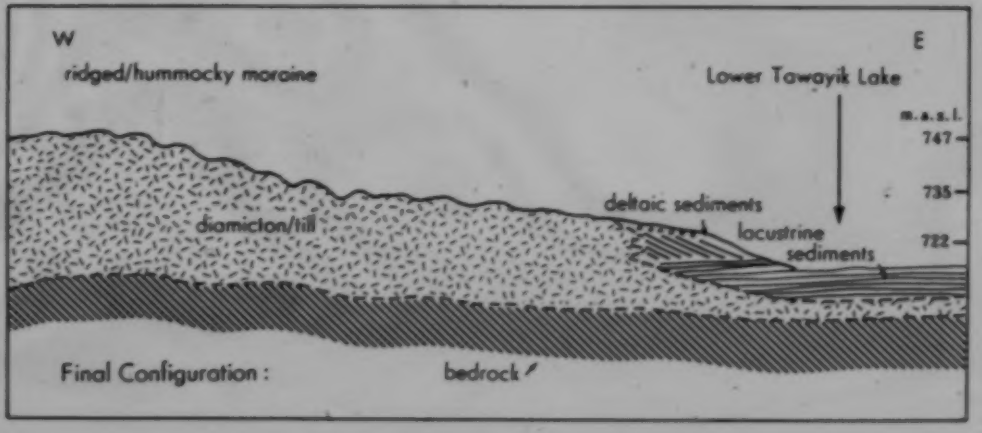


Figure 4.41 The interpreted formation events for Zone Four

The imbricated cobble gravels are interpreted as subaerial, channel deposits. In the late stages of lake-filling numerous small distributary channels incised into the delta surface (Figure 4.41, Stage 2). Directional evidence indicates flow was slightly oblique to the flow direction which deposited the ripple-drift cross-laminations.

5. SUMMARY AND CONCLUSIONS

5.1 Introduction

Preceding chapters have outlined the observations and interpretations of site-specific landform/sediment units within the study area. A genesis for each of these characteristic morainic and glaciofluvial/glaciolacustrine landforms was suggested. Here, the genetic and geochronologic associations of the landforms/landscape are summarized, emphasizing relationships pertinent to the regional deglacial and postglacial chronology.

5.2 The Distribution of Surficial Deposits

The surficial geology map of the Edmonton area (NTS 83H) is at such a scale (1:250,000) that it cannot provide detailed information on surficial deposits and landform associations for the study area. Accordingly, maps of the surficial deposits and morphogenetic units were constructed from aerial photograph interpretation, field reconnaissance and, combined road cut and backhoe excavation description/interpretation, plus drilling log interpretation (Figure 5.1). The man-made exposures allowed detailed observation of the variability of the surficial deposits in the upper few metres. The boreholes provided important information as to the irregularity of the drift thickness and vertical column stratigraphy.

The surficial deposits of the study area include:

a. till/diamicton sheets and hummocky moraine,
b. glaciofluvial sediments, with associated eskers, kames, deltas, and meltwater channels,
c. glaciolacustrine sediments, from both proglacial and superglacial environments, and
d. a variable thickness of loess.

Recent deposits include peat and organic mud found in depressions and contemporary lake basins. Minor colluvial and alluvial sediments have also been deposited in Holocene time.

DESCRIPTIVE KEY

	Genetic Composition	Predominant Sedimentary Environment	Surface Expression	Predominant Landforms
	Contemporary lacustrine	contemporary lakes and ponds		
	Undifferentiated Organic	fens and bogs	level	
	Glaciolacustrine	proglacial / superglacial lakes	level	lacustrine plains
	Glaciolacustrine	superglacial lake	undulating	discontinuous lacustrine mantle/deltas
	Glaciofluvial	englacial/superglacial channel	hummocky/pitted	kame complex/eskers/deltas
	Till	base of active ice	level	ground moraine
	Till / Diamicton	disintegrating stagnant ice	hummocky	hummocks
	Till / Diamicton	disintegrating stagnant ice	lineur ridged	ridges
	Till / Diamicton	disintegrating stagnant ice	circular ridged	prairie mounds
			disturbed	

definitive unit boundary

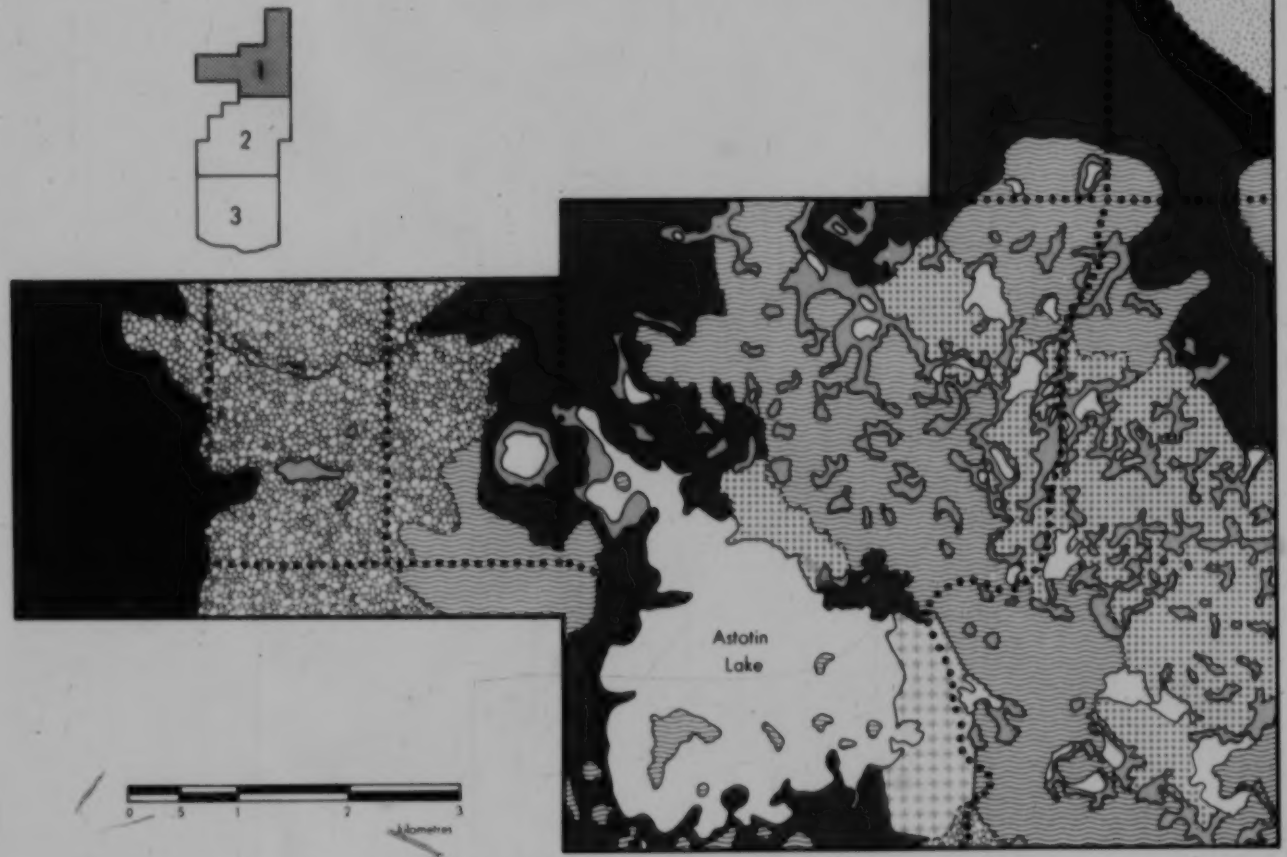
tentative unit boundary

highway

road

trail

Figure 5.1a Surficial deposits and morphogenetic units



DESCRIPTIVE KEY

Genetic Composition	Predominant Sedimentary Environment	Surface Expression	Predominant Landforms
Contemporary Lacustrine	contemporary lakes and ponds		
Undifferentiated Organic	fens and bogs	level	
Glaciolacustrine	proglacial / superglacial lakes	level	lacustrine plains
Glaciolacustrine	superglacial lake	undulating	discontinuous lacustrine mantle/deltas
Glaciofluvial	englacial/superglacial channel	hummocky, pitted	kame complex/eskers/deltas
Till	base of active ice	level	ground moraine
Till / Diamicton	disintegrating stagnant ice	hummocky	hummocks
Till / Diamicton	disintegrating stagnant ice	linear ridged	ridges
Till / Diamicton	disintegrating stagnant ice	circular ridged	prairie mounds
		disturbed	

definitive unit boundary

tentative unit boundary

highway

road

trail

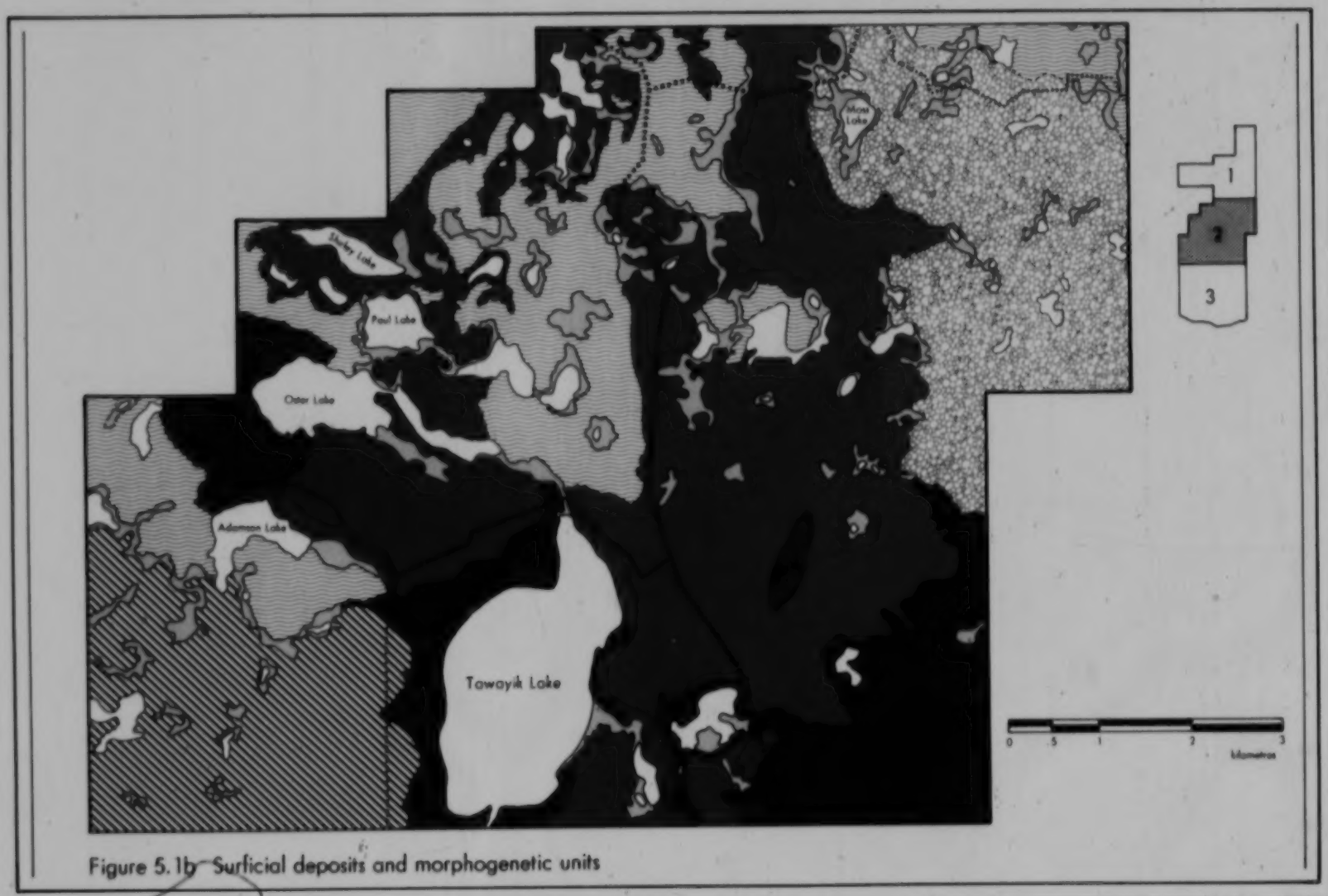


Figure 5.1b Surficial deposits and morphogenetic units

DESCRIPTIVE KEY

	Genetic Composition	Predominant Sedimentary Environment	Surface Expression	Predominant Landforms
	Contemporary Lacustrine	contemporary lakes and ponds		
	Undifferentiated Organic	fens and bogs	level	
	Glaciolacustrine	proglacial / superglacial lakes	level	lacustrine plains
	Glaciolacustrine	superglacial lake	undulating	discontinuous lacustrine mantle/deltas
	Glaciofluvial	englacial/superglacial channel	hummocky/pitted	kame complex/eskers/deltas
	Till	base of active ice	level	ground moraine
	Till / Diamicton	disintegrating stagnant ice	hummocky	hummocks
	Till / Diamicton	disintegrating stagnant ice	linear ridged	ridges
	Till / Diamicton	disintegrating stagnant ice	circular ridged	prairie mounds
			disturbed	

definitive unit boundary

tentative unit boundary

highway

road

trail

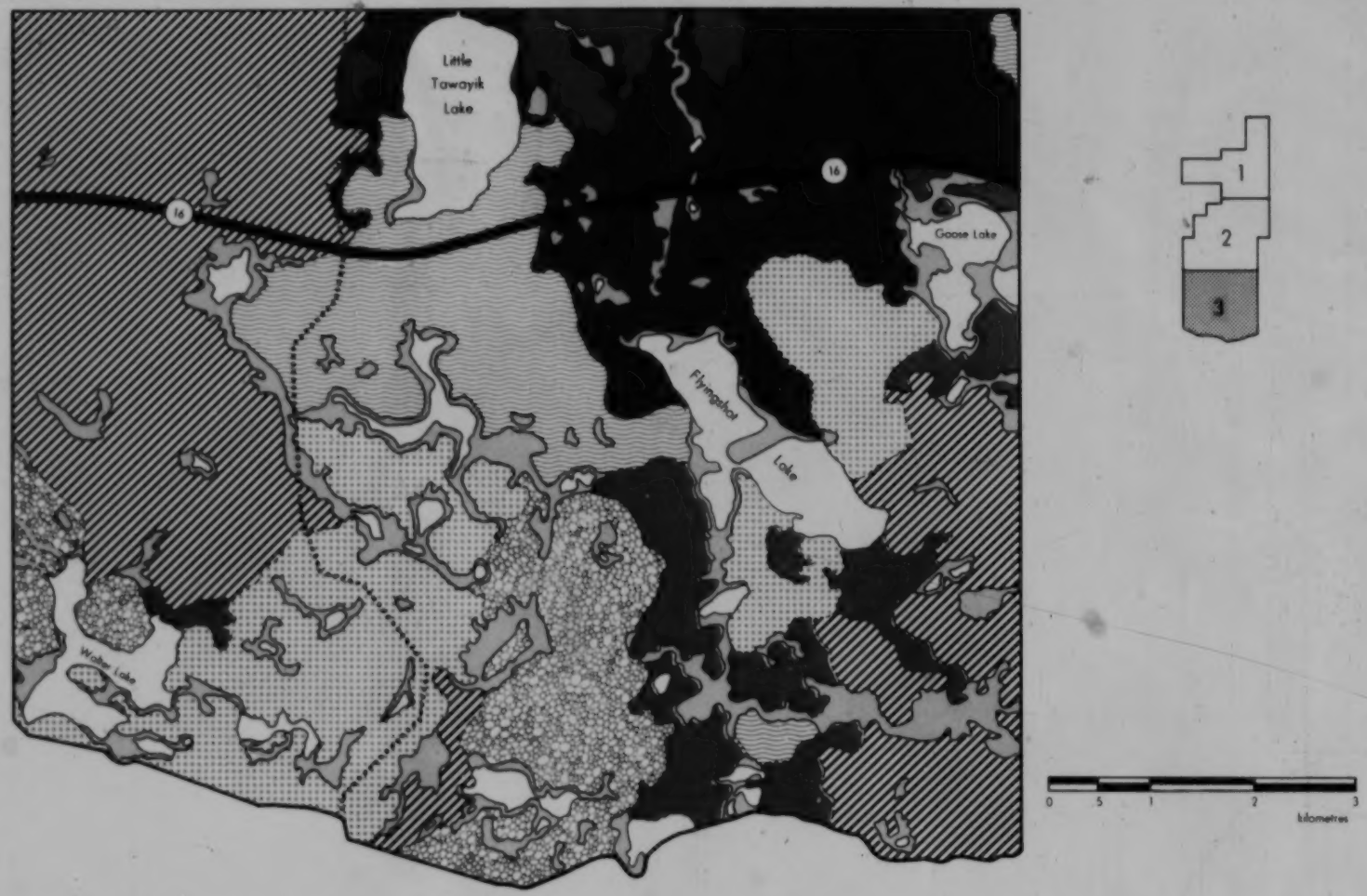


Figure 5.1c Surficial deposits and morphogenetic units

Four distinct genetic types of till/diamicton are differentiated on the basis of matrix texture, structure, and geomorphic attributes. **Lodgement till** is limited to the northeastern corner of the study area where it forms a thin till mantle over bedrock. Two types of melt-out till are recognized; **basal melt-out till** and **ablation melt-out till**. Both melt-out tills, with associated local lenses or units of sorted sediments are compact and have a relatively strong preferred orientation of coarse clasts. Underlying hummocky moraine, they occur lowermost in the stratigraphic sequence. Fourthly, **sediment flow diamicton** has a characteristic *flow appearance*, is friable, and often contains incorporated pond sediments. The preferred orientation of coarse clasts is, not surprisingly, poorly developed. This diamicton usually comprises the uppermost facies and underlies hummocky moraine.

Highly variable textural qualities, plus primary, penecontemporaneous and secondary structures, are represented within the glaciofluvial/glaciolacustrine sediments. Primary structures range from fine-grained rhythmites to coarse-grained and imbricated cobble gravels. The secondary structures are predominantly expressed as faults. Each of the different fault types is attributed primarily to the melting of confining or buried ice.

5.3 Landform Associations and Geochronology

Combining the previously discussed descriptions and interpretations with the surficial deposits maps it is apparent that a variety of depositional environments existed in the study area. The present surface configuration is mainly attributed to the geomorphic processes which occurred during late Wisconsinan deglaciation. However, the preglacial topography, at least one earlier glacial episode and climatically-induced processes during postglacial times have also influenced, although to a much lesser extent, the creation of the contemporary landscape.

This discussion stresses the geomorphic processes and events which occurred within the Edmonton region generally, and the study area specifically, during and following the last deglaciation. Very few details are known about earlier Quaternary processes and events except that at least two glacial episodes are represented by two separate tills. At one location in the study area two tills, possibly equivalent to those above, are separated

by lacustrine sediments. The time-spans for both the glacial and *nonglacial* intervals are unknown, although the *nonglacial* interval, as represented by the intertill lacustrine sediments, is at least as old as 26,000 years BP (see Section 3.3.2.4).

Geochronology is used as a *connecting thread* to outline the landform genesis and landscape evolution of the study area. Several regional geomorphic events and climatic phases are considered to be correlative with the creation of particular landscape elements within the study area (Table 5.1). Several developmental stages are presented and discussed in the following pages. The basic framework for this discussion follows the work of St. Onge (1972), Westgate *et al.*, (1976) and Christiansen (1980).

5.3.1 Stage One: *Circa* 14,000 years B.P. to *circa* 12,000 years B.P.

Progressive downslope retreat of the Laurentide ice front to the northeast enabled a sequence of proglacial lakes to develop along its margin. At approximately 14,000 years B.P. Glacial Lake Leduc was in existence (Figure 5.2a). By 12,500 years B.P. water from Glacial Lake Leduc had drained southeast through the Gwynne Outlet into the Battle River system, eventually reaching Glacial Lake Saskatchewan. Glacial Lake St. Albert, the reduced phase of Glacial Lake Leduc, was bounded by the retreating ice and also the stagnant ice in the study area (Figure 5.2b). The North Saskatchewan River constructed a large delta into this lake west of Edmonton. Within the study area a delta (see Section 4.3.2.3) formed as superglacial meltwater flowed into this lake (Figure 5.2b, Site a).

5.3.2 Stage Two: *Circa* 12,000 years B.P. to *circa* 11,000 years B.P.

Further ice retreat allowed Glacial Lake Bruderheim to form immediately north of Elk Island National Park. This glacial lake became the new base-level for the North Saskatchewan River, enabling a second, lower delta to be constructed. In the study area, the lake water, impounded between the retreating ice and the stagnant ice, deposited lacustrine sediments. The prevailing northwest winds blew ice bergs, with encorporated debris, from the receding ice mass across the lake where they accumulated in the embayment (Figure 5.2c). The material from these blocks was deposited synchronously with lacustrine deposition (see Section 4.3.3.4).

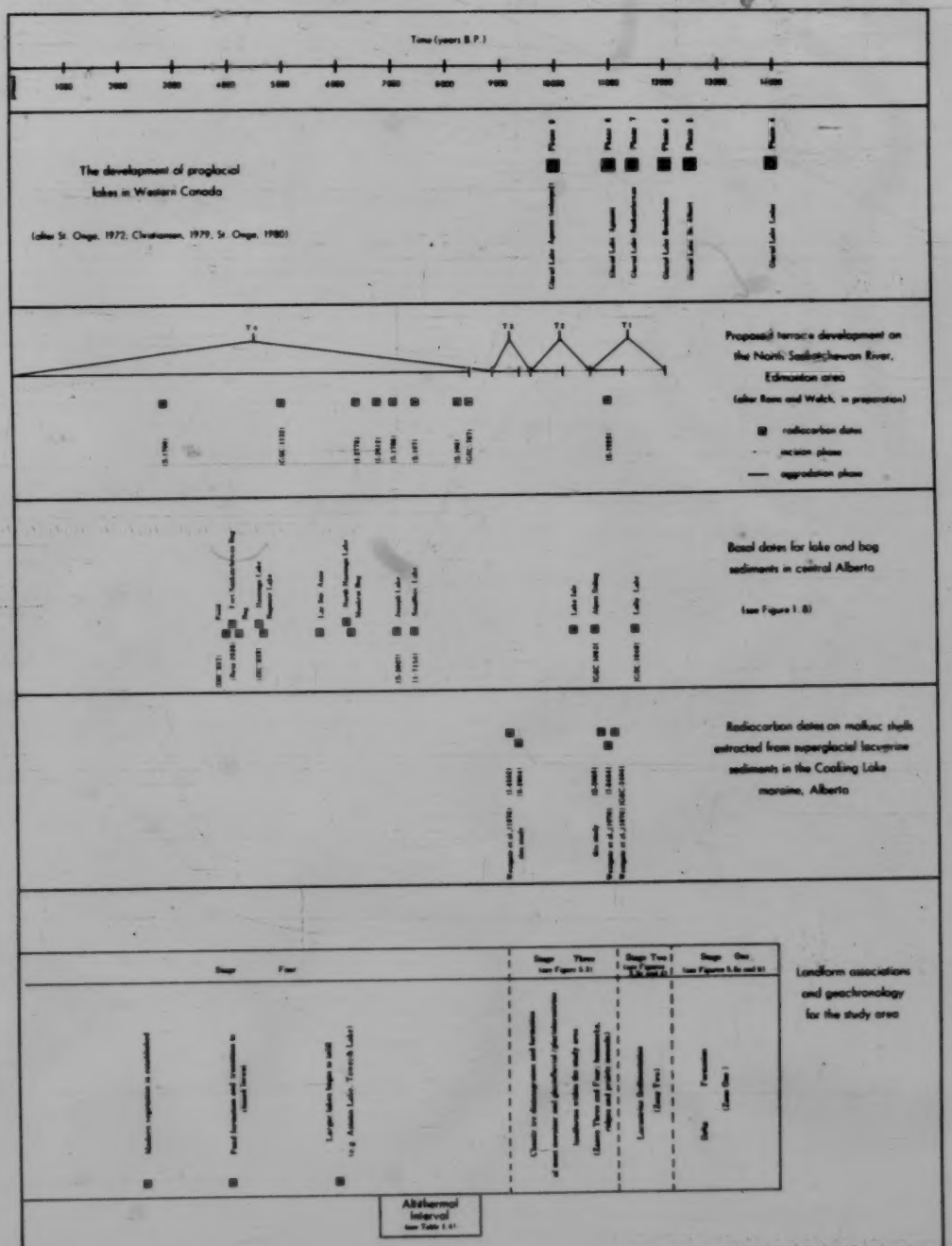

Time (years B.P.)
The development of proglacial lakes in Western Canada
(after St. Onge, 1972; Christiansen, 1979; St. Onge, 1980)
Proposed terrace development on the North Saskatchewan River, Edmonton area
(after Rees and Welch, in preparation)
radiocarbon dates
incision phase
aggradation phase
Basal dates for lake and bog sediments in central Alberta
(see Figure 1.8)
Radiocarbon dates on mollusc shells extracted from superglacial lacustrine sediments in the Cooking Lake moraine, Alberta
Stage
Phase
Altithermal Interval
Landform associations and geochronology for the study area

Table 5.1 Regional geomorphic events and climatic trends are directly correlative with the creation of particular landscape elements within the study area

Figure 5.2 Progressive deglaciation with the development of ice-dammed lakes and associated deltas in the Edmonton Region: Stage One

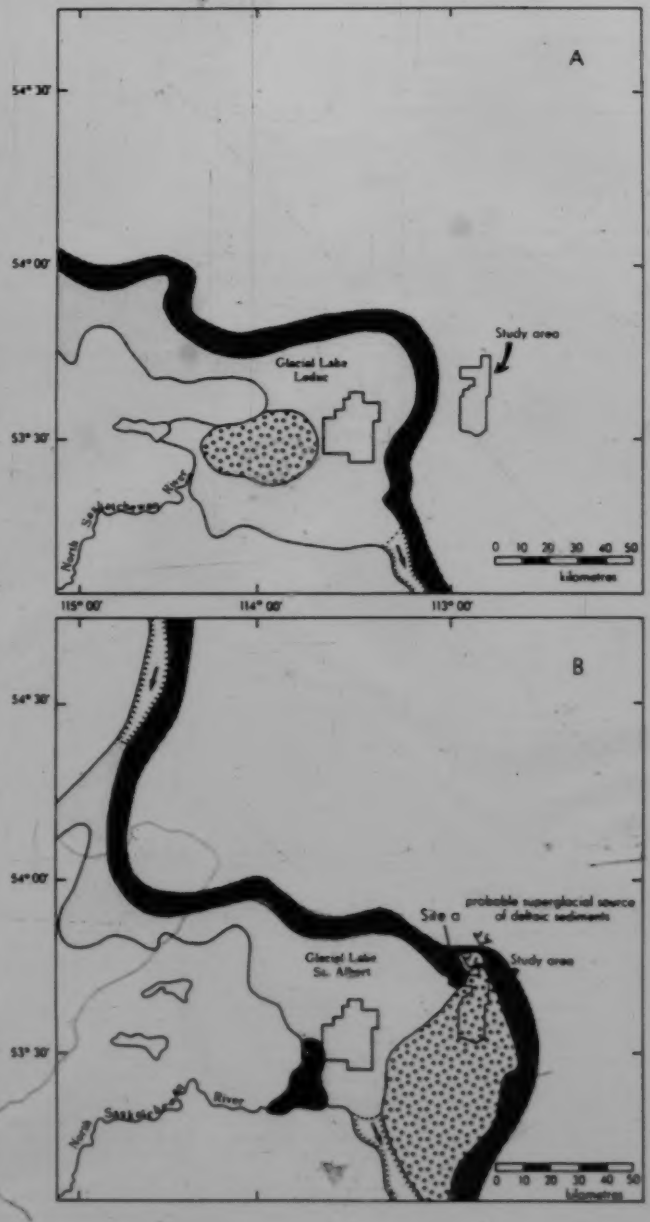


Figure 5.2a
The development of Glacial Lake Leduc as ice retreated towards the northeast

Circa 14,000 years B.P.

[adapted from Phase 4 of St. Onge (1972)]

Legend (A and B):

- Receding ice front
- Stagnant ice
- Glacial lake
- Outlet, meltwater channel
- Delta

Figure 5.2b

The development of Glacial Lake St. Albert and the delta immediately west of Elk Island National Park (see Zone One; Section 4.3.2)

Circa 12,500 years B.P.

[adapted from Phase 5 of St. Onge (1972)]

Figure 5.2 (continued) Progressive deglaciation with the development of ice-dammed lakes and associated deltas in the Edmonton Region: Stage Two

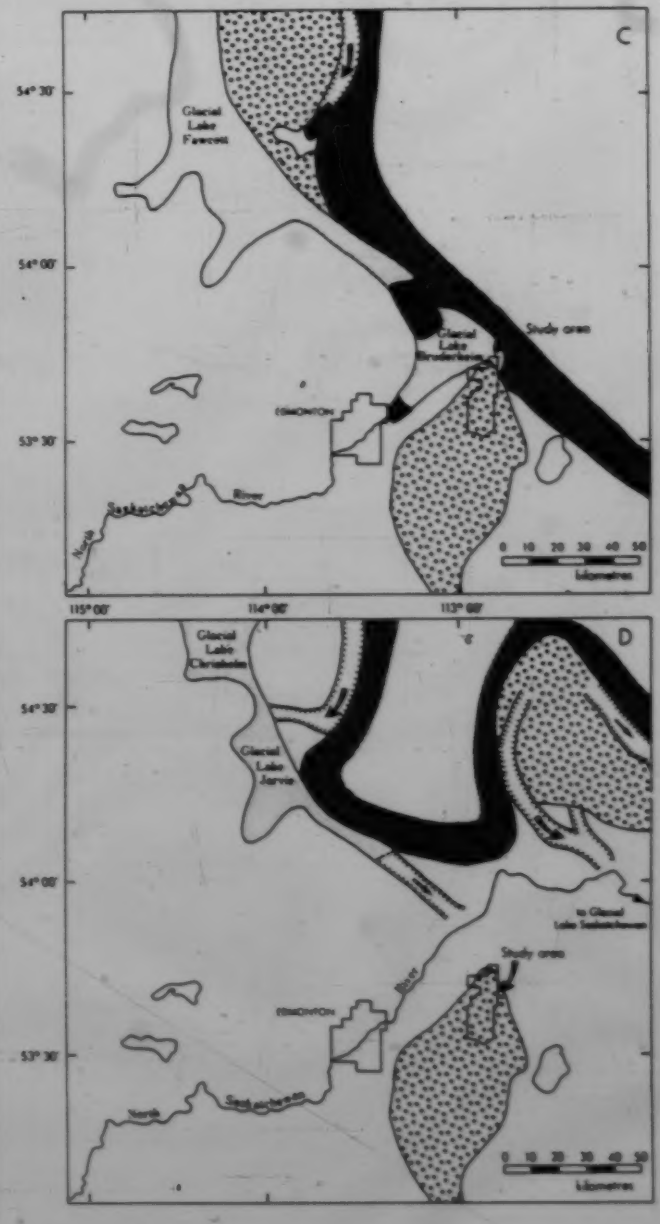


Figure 5.2c

The development of Glacial Lake Bruderheim and the deposition of lacustrine sediments and ice-rafted debris immediately north of Elk Island National Park
(see Zone Two; Section 4.3.3)

Circa 12,000 years B.P.

[adapted from Phase 6 of St. Onge (1972)]

Legend (C and D):

- Receding ice front
- Stagnant ice
- Glacial lake
- Outlet, meltwater channel
- Delta

Figure 5.2d

Glacial Lake Bruderheim has drained via the Vermilion Spillway to Glacial Lake Saskatchewan

Circa 11,500 years B.P.

[adapted from Phase 7 of St. Onge (1972)]

By 11,500 years B.P. the ice had retreated to the north and east of the study area (Figure 5.2d). Glacial Lake Bruderheim had drained via the Vermilion Spillway and the North Saskatchewan River was able to flow unimpeded to Glacial Lake Saskatchewan executing its initial incision through the Edmonton district (Table 5.1). Some stagnant ice remained in the study area, isolated and buried under a thick superglacial debris cover. Here, landform formation was limited because till deposition was largely by basal melt-out (see Section 3.1.2.3).

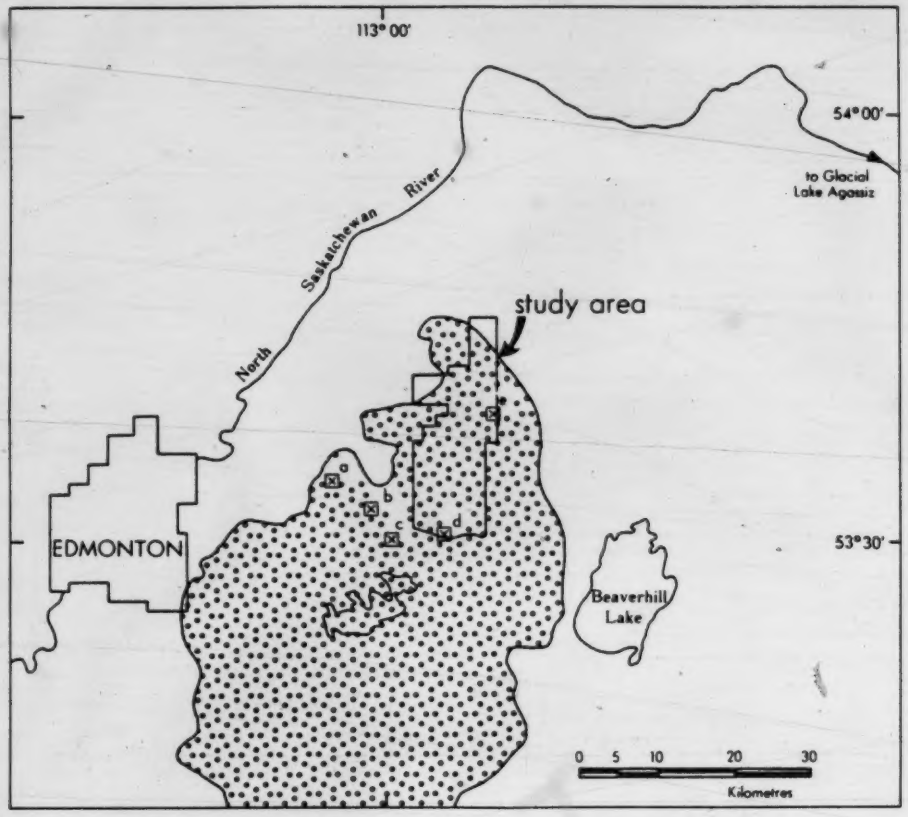
5.3.3 Stage Three: *Circa* 11,000 years B.P. to *circa* 9,000 years B.P.

By 11,000 years B.P. most of the Edmonton region was ice-free except for the buried, stagnant ice of the Cooking Lake moraine (Figure 5.3). At that time a warming trend with increased precipitation was in progress (Emerson, 1983). Also, the large contemporary lakes had begun to fill.

Stage Three represented the time of most significant morainic and glaciofluvial/glaciolacustrine landform formation in Elk Island National Park. For a time prior to 11,000 years B.P. the superglacial debris cover had been stable, inhibiting marked ablation of the buried ice. The development of small thaw lakes/ponds in the superglacial zone eventually ruptured this stable debris promoting the evolution of more pronounced local relief. Disintegration of the stagnant ice ensued, allowing relief inversion of morainic landforms to proceed. The let-down theory of landform formation best explains the genesis of the described hummocks and prairie mounds of the study area (see Chapter 3). There are numerous examples of superglacial lacustrine sediments occupying the central core of hummocks. The sediments are usually draped or distorted by sediment flow diamicton (see Section 3.3.2.1). These observations indicate that mass movement in the superglacial environment was mainly responsible for filling in the thaw lakes/ponds. As material accumulated in the depressions the ice-cored flanks, now having a thinner debris cover, were exposed to increased rates of surface ablation. Therefore, with final melting, raised areas (which were once depressions) remained flanked by intervening depressions. Dependent upon the configuration of the buried ice below the original depressions either hummocks (see Section 3.3.2) or prairie mounds (see Section 3.3.3) developed. Ridge forms can be explained in a similar manner. In this case, however, the original depressional

Figure 5.3 Stage Three : Circa 11,000 years B.P. to circa 9,000 years B.P.
This stage represents the time of most significant morainic and glaciofluvial/glaciolacustrine landform formation within the study area. The time interval was determined from radiocarbon dates on molluscs from superglacial lacustrine sediments

[adapted from Phase 8 of St. Onge (1972)].



Legend

Stagnant ice

Radiocarbon dates

a	9,050 ± 150 years B.P.	[I - 4552]	Westgate et al., (1976)
b	10,880 ± 155 years B.P.	[I - 8484]	Westgate et al., (1976)
c	10,900 ± 190 years B.P.	[GSC - 2404]	Westgate et al., (1976)
d	9,155 ± 310 years B.P.	[S - 2084]	present study
e	10,825 ± 240 years B.P.	[S - 2085]	present study

areas were linear, probably developing along crevasses as the stagnant ice broke up. Shells found within the superglacial lacustrine sediments were radiocarbon dated from about 10,900 years B.P. to 9,050 years B.P. (Table 5.1 and Figure 5.3) and indicate that this stage of landform formation lasted at least 2,000 years.

Synchronous with morainic landform formation was the development of large superglacial and inframarginal lakes. Glaciolacustrine sediments now mark their extent, thinning to only a shallow veneer over till around their margins (Figure 5.1). Meltwater streams issuing into these lakes constructed small deltas (see Section 4.3.5). A kame complex (see Section 4.3.4) developed in the central part of Elk Island National Park. Here, upon final melting of buried ice, rapid shifting of glaciofluvial channels and lakes/ponds produced an assemblage of hummocks and depressions dominated by stratified drift and sediment flow diamicton.

5.3.4 Stage Four: *Circa* 9,000 years B.P. to present

By 9,000 years B.P. the glacigenic deposits were more-or-less in their present configuration and all buried ice had now been removed. By 6,000 years B.P. the Altithermal interval of western Canada had ended. A trend towards cooler and moister conditions prevailed and by 4,000 years B.P. the climatic change had stimulated a vegetation transition from open parkland to closed forest conditions and pond formation within the study area (Table 5.1). The modern vegetation and landscape elements were probably fully established by 2,500 years B.P.

5.4 Conclusion

This study has shown that within the northern portion of the Cooking Lake moraine diverse types of morainic and glaciofluvial/glaciolacustrine landforms occur. All of these are characteristic of hummocky moraine tracts. The predominant landforms and associated sediments reflect the chaotic disintegration of a large mass of stagnant glacial ice.

Several conclusions are drawn from the research. First, the processes responsible for the creation of the landforms within the study area took place primarily in

the superglacial environment. Sedimentation, resedimentation and finally deposition were controlled, to a large extent, by the presence of an unequal, ice-surface, debris distribution and buried stagnant ice. Secondly, the observations and interpretations presented previously (for example, the dominance of sediment flow diamicton with frequent inclusions of water-laid sediments) indicate that the genesis of the morainic landforms was, in most cases, by *let-down* and *relief inversion*. This is not to say, however, that all morainic landforms within *hummocky moraine* tracts evolved in this manner. Indeed, the literature has shown well that other formation mechanisms do occur.

Thirdly, the glaciofluvial/glaciolacustrine landforms were formed in an *ice-contact* environment. The characteristically pitted morphologic expression, and the common occurrence of secondary deformation structures within the sediments, attest to the post-depositional removal of buried or supporting ice.

Finally, the geochronology outlined here for the study area fits well with established interpretations of the late Quaternary events of central Alberta. Radiocarbon dating on mollusc shells revealed that the most significant landform formation took place between *circa* 11,000 years B.P. and *circa* 9,000 years B.P. The significance of this rests in the fact that buried stagnant ice remained in the study area long after the retreating, active ice front of the Laurentide ice sheet lay far to the north and east of the Edmonton area. It appears that from *circa* 9,000 years B.P. to the present the later, more subtle, evolution of the landscape related mainly to climatic changes (e.g. those of the Altithermal interval) where trends in temperature and precipitation affected the lake hydrology and vegetation succession.

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6. APPENDIX 1

6.1 Till Fabrics: Theory and Analytic Methods

6.1.1 Introduction

Various authors have noted transverse and parallel orientations of tillstones with respect to the former ice flow direction. A number of explanations exist for both of these fabric modes plus the frequently observed bimodal fabrics. Consistently parallel or transverse, and bimodal fabrics have been observed for lodgement and melt-out tills (Holmes, 1941; Harrison, 1957; Glen *et al.*, 1957; Harris, 1969; Boulton, 1970a, 1971; Evenson, 1971). These variations have been attributed to stone geometry (Holmes, 1941; Andrews, 1971b), stone collisions and concentration (Glen *et al.*, 1957; Evenson, 1971), glacier flow regime (Harrison, 1957; Boulton, 1970a, 1971), non-random primary entrainment (Glen *et al.*, 1957), time-duration of entrainment (Glen *et al.*, 1957) and secondary flow cells (Shaw and Freschauf, 1973). In flow tills parallel and transverse preferred orientations are defined with respect to direction of till flow, not glacier flow direction (Mark, 1974; Lawson, 1979).

Some authors have paid particular attention to a preferred upglacier plunge (Harrison, 1957; Glen *et al.*, 1957; McClintock and Dreimanis, 1964; Boulton, 1971) but have attributed this plunge to different reasons. Evenson (1971) grouped these into three theories; ice-shear, slope, and till-shear.

The fabrics can also be post-depositionally reoriented by the weight of overlying ice (Hoppe, 1952), advance of another ice sheet (McClintock and Dreimanis, 1964; Ramsden and Westgate, 1971) and debris flows (Boulton, 1972; Mark, 1974; Lawson, 1979). Reorientation may even occur in response to present-day processes of pedogenesis, mass movement, frost penetration and biotic agencies (Straw, 1968). Therefore, final particle orientation need not occur within the ice and, in fact may develop later as a response to many variables.

Till fabric analysis is therefore used to assist in the interpretation of former glacier flow directions and/or the geomorphic processes involved in till formation. However,

care must always be exercized in strictly applying till fabric information. It should only augment the other indicators and the genetic classification of till.

6.1.2 Data Display

The data from each of the sample sites were first displayed using two-dimensional, mirror-image, rose diagrams which portray the number of pebbles within 10° azimuthal classes. This technique has the advantage of conveying a strong visual impression. However, there is a loss of information as the plunge data are not incorporated. Also, the mirror-image tends to artificially accentuate the strength of the fabric and the visual impact can be altered substantially should the class interval or starting point be altered (Andrews, 1971a).

The combined directional and plunge data were thus integrated into three-dimensional, contoured, equal-area projections. These computer-generated, circular diagrams were developed using a method developed by Kamb (1959). Azimuthal degrees are calibrated around the circumference while plunge values increase from 0° at the perimeter to 90° at the centre of the circle. Kamb's (1959) method requires that a pre-determined grid network be placed over an equal-area projection. A small open circle, the area of which is 3 percent of the area of the larger circle, is then centred over each of the grid points and the number of data points falling within this counting circle is recorded. The distribution of these numbers, obtained from successive counting circles, can be manually contoured. However, a standardized format, which is both independent of the sample size and may be applied to all studies, is necessary. This is achieved by expressing the contour interval in standard deviations (Andrews, 1971a). The commonly selected contour interval is two standard deviations. Contoured fabric diagrams again provide a good visual impression of till fabric information. However, like conventional rose diagrams some loss of information is expected as data are grouped into class intervals.

6.1.3 Statistical Treatment of the Data

Krumbein (1939) was the first to realize that more than just a visual evaluation of till fabric data was sometimes needed. In order to generalize about the population of till particles at an exposure, and also to allow controlled comparison between fabric sites in terms of mean orientation, strength of this orientation and the degree of clustering about the principle axis, a number of complementary statistical analyses were used. As each pebble measurement is considered to represent a unit vector, addition of these projections gives the azimuth and plunge of the resultant vector. The direction of this resultant vector represents the mean orientation and the length indicates the vector strength (R) (Fisher, 1953; Watson, 1966; Steinmetz, 1962).

Statistics produced by the eigenvalue analyses of axial orientation data are an effective means of representing till fabric information (Mark, 1974). Because the individual observations represent unit vectors, eigenvalues (1, 2, 3) can be computed from a 3 X 3 matrix of the sums of cross products of their directional cosines (Watson, 1966; Mark, 1973; Woodcock, 1977). The corresponding eigenvectors (V1, V2, V3 respectively) are also determined. V1 shows the axis of maximum clustering and therefore represents the distribution mean (Woodcock, 1977). Hence, the primary mode of the till fabric, with principle azimuth and plunge, is implied (Mark, 1974). As the eigenvalues must sum to the sample number (1+ 2+ 3 = N) they may be normalized to the form j / N = Sj. Therefore, S1 + S2 + S3 = 1 and each measures the degree of clustering about their respective eigenvector (Woodcock, 1977). S1 ultimately measures the degree of axial clustering about the mean axis and is consequently a very powerful indicator of the strength of the preferred orientation of the till stones.

7. APPENDIX 2

7.1 Radiocarbon dates at Site H-BR-45

(see pp. 102-105)

Field Sample Number: EIP-DJ-A2

Laboratory Number: S-2159

Radiocarbon Age: 25,550 yrs. BP

Material: wood fragments, grasses (species unknown)

Enclosing Material: lacustrine silt and clay

Geographic Location: 200 metres south of Astotin Lake, Elk Island National Park, Alberta.

Latitude: 53° 39' 58" N

Longitude: 112° 52' 00" W

NTS Sheet Number: 83 H/10

Grid Location: 766477

Details of Collection Site: The sample was extracted during an exploration drilling programme. The borehole site was on the top of a morainic hummock approximately 200 metres south of, and 8 metres higher than, Astotin Lake.

Local Stratigraphic Relations: The sample was retrieved from an auger depth of 11.5 metres. The thick silt and clay layer (5 m) occurs stratigraphically between two tills. Bedrock was reached at a depth of 29 metres.

Significance of the Sample: Since the silt and clay layer is sandwiched between two tills it probably represents lacustrine sedimentation prior to the last glacial episode. Therefore, the radiocarbon date gives the minimum age for a nonglacial period separating two episodes of glacial activity in the area.

Field Sample Number: EIP-DJ-A2

Laboratory Number: S-2160

Radiocarbon Age: 26,000 + 1100 years BP

Material: wood fragments, grasses (species unknown)

Enclosing Material: lacustrine silt and clay

Geographic Location: 200 metres south of Astotin Lake, Elk Island National Park, Alberta.

Latitude: 53° 39' 58" N

Longitude: 112° 52' 00" W

NTS Sheet Number: 83 H/10

Grid Location: 766477

Details of Collection Site: The sample was extracted during an exploration drilling programme. The borehole site was on the top of a morainic hummock approximately 200 metres south of, and 8 metres higher than, Astotin Lake.

Local Stratigraphic Relations: The sample was retrieved from an auger depth of 14.5 metres. The thick silt and clay layer (5 m) occurs stratigraphically between two tills. Bedrock was reached at a depth of 29 metres.

Significance of the Sample: Since the silt and clay layer is sandwiched between two tills it probably represents lacustrine sedimentation prior to the last glacial episode. Therefore, the radiocarbon date gives the minimum age for a nonglacial period separating two episodes of glacial activity in the area.